MARINE COMPOSITES

Second Edition

Eric Greene Associates

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Introduction

The evolution of composite material boat construction has created the need to evaluate the basic design tools that are used to create safe marine structures. As materials and building practices improve, it is not unreasonable to consider composite construction for vessels up to 100 meters (approx 330 feet). Although design principles for ship structures and composite materials used for aerospace structures are mature as individual disciplines, procedures for combining the technologies are at an infancy. This second edition of ***MARINE COMPOSITES*** explores the technologies required to engineer advanced composite materials for large marine structures. As with the first edition of ***MARINE COMPOSITES***, Applications, Materials, Design Performance and Fabrication are addressed.

This edition of ***MARINE COMPOSITES*** is the outgrowth of Ship Structure Committee (SSC) reports SSC-360 and SSC-403. The U.S. Navy's NSWC, Carderock Division also funded an update of the Applications and Fabrication sections. The author is also indebted to builders that responded to surveys on materials and processes. Individuals who served on the SSC Project Technical Committee provided valuable input throughout the duration of the project. In particular, Dr. Gene Camponeschi, Dr. Robert Sielski, Loc Nguyen, Dave Heller, Bill Lind, George Wilhelmi, Chuck Rollhauser and Ed Kadala have given insight into the design of marine composite structures based on their own experience. Art Wolfe and Dr. Ron Reichard of Structural Composites; Tom Johannsen of ATC Chemical Corporation; and Ken Raybould of Martech also contributed with data and review.

Background

The origins of composite material concepts date back to the builders of primitive mud and straw huts. Modern day composite materials were launched with phenolic resins at the turn of the century. The start of fiberglass boatbuilding began after World War II. The U.S. Navy built a class of 28-foot personnel craft just after the war based on the potential for reduced maintenance and production costs.

During the 1960s, fiberglass boatbuilding proliferated and with it came the rapid increase in boat ownership. The mass appeal of lower cost hulls that required virtually no maintenance launched a new class of boaters in this country. Early FRP boatbuilders relied on "build and test" or empirical methods to guarantee that the hulls they were producing were strong enough. Because fiberglass was a relatively new boatbuilding material, designers tended to be conservative in the amount of material used.

In 1960, Owens-Corning Fiberglas Corporation sponsored the naval architecture firm, Gibbs & Cox to produce the ***"Marine Design Manual for Fiberglass Reinforced Plastics."*** This book, published by McGraw-Hill, was the first fiberglass design guide targeted directly at the boatbuilding industry. Design and construction methods were detailed and laminate performance data for commonly used materials were presented in tabular form. The guide proved to be extremely useful for the materials and building techniques that were prevalent at the time.

As the aerospace industry embraced composites for airframe construction, analytical techniques developed for design. The critical nature of composite aerospace structures warrants significant analysis and testing of proposed laminates. Unfortunately for the marine industry, aerospace laminates usually consist of carbon fiber and epoxy made from reinforcements pre-impregnated with resin (prepregs) that are cured in an autoclave. Costs and part size limitations make these systems impractical for the majority of marine structures. Airframe loads also differ from those found with maritime structures. However, in recent times the two industries are coming closer together. High-end marine manufacturing is looking more to using prepregs, while aircraft manufacturers are looking to more cost-effective fabrication methods.

MARINE COMPOSITES strives to be an up-to-date compendium of materials, design and building practices in the marine composites industry - a field that is constantly changing. Designers should seek out as much technical and practical information as time permits. In recent years, a very valuable source for design guidance has been specialized conferences and courses. Composites oriented conferences, such as those sponsored by the Society of the Plastics Industry (SPI) and the Society for the Advancement of Materials Processing and Engineering (SAMPE), have over the years had a few marine industry papers presented at their annual meetings. Ship design societies, such as the Society of Naval Architects and Marine Engineers (SNAME) and the American Society of Naval Engineers (ASNE) also occasionally address composite construction issues in their conferences and publications, Indeed ASNE devoted an entire conference to the subject in the Fall of 1993 in Savannah. The Ship Structure Committee sponsored a conference on "*The Use of Composite Materials in Load-Bearing Marine Structures*," convened September, 1990 by the National Research Council. SNAME has an active technical committee, HS-9, that is involved with composite materials. The Composites Education Association, in Melbourne, Florida hosts a biennial conference called Marine Applications of Composite Materials (MACM). The five MACM conferences to date have featured technical presentations specific to the marine composites industry.

Robert J. Scott, of Gibbs & Cox, has prepared course notes for the University of Michigan based on his book, ***"Fiberglass Boat Design and Construction,"*** published in 1973 by John deGraff. An update of that book is now available through SNAME. In 1990, the Ship Structure Committee published SSC-360, ***"Use of Fiber Reinforced Plastics in the Marine Industry"*** by the author of this publication. That report serves as a compendium of materials and construction practices through the late 1980s. In the United Kingdom, Elsevier Science Publishers released the late C.S. Smith's work, ***"Design of Marine Structures in Composite Materials."*** This volume provides an excellent summary of Smith's lifelong work for the British Ministry of Defence, with a thorough treatment of hat-stiffened, composite panels.

Relevant information can also be found scattered among professional journals, such as those produced by SNAME, ASNE, the Composite Fabricators Association (CFA), SAMPE and industry publications, such as *Composites Technology*, *Composite Design & Application* and *Reinforced Plastics*. *Professional Boatbuilder*, published by WoodenBoat Publications, Inc, Brooklin, ME is emerging as the focal point for technical issues related to the marine composites field.

Eric Greene

Recreational Marine Industry

Over 30 years of FRP boat building experience stands behind today's pleasure boats. Complex configurations and the advantages of seamless hulls were the driving factors in the development of FRP boats. FRP materials have gained unilateral acceptance in pleasure craft because of light weight, vibration damping, corrosion resistance, impact resistance, low construction costs and ease of fabrication, maintenance and repair.

Fiberglass construction has been the mainstay of the recreational boating industry since the mid 1960s. After about 20 years of development work, manufacturers seized the opportunity to mass produce easily maintained hulls with a minimum number of assembled parts. Much of the early FRP structural design work relied on trial and error, which may have also led to the high attrition rate of startup builders. Current leading edge marine composite manufacturing technologies are driven by racing vessels, both power and sail.

Racing sail and power events not only force a builder to maximize structural performance through weight reduction, but also subject vessels to higher loads and greater cycles than would normally be seen by vessels not operated competitively. Examples of raceboat technology and some other firms that have carved out nitches in the industry are presented for illustrative purposes. This is by no means an exhaustive list of manufacturers who are doing innovative work in the field.

Racing Powerboats

Racing powerboats employ advanced and hybrid composites for a higher performance craft and driver safety. Fothergill Composites Inc., Bennington, VT, has designed, tested and manufactured a safety cell cockpit for the racing boat driver. The safety cell is constructed of carbon and aramid fibers with aramid honeycomb core. This structure can withstand a 100 foot drop test without significant damage. During the *Sacramento Grand Prix*, three drivers in safety cell equipped boats survived injury from accidents. [1-1]

Ron Jones Marine

Ron Jones Marine, located in Kent WA, manufactures high-tech hydroplanes for racing on the professional circuit. Ron Jones, Sr. has been building racing hydroplanes since 1955. In the 1970s, these classes switched to composite construction. Today, Ron and his son build specialized craft using prepreg reinforcements and honeycomb coring. Over 350 boats have been built in Jones' shop.

Many innovations at the Ron Jones shop focus on driver safety for these boats that race in excess of 200 mph. To control airborne stability, Jones builds a tandem wing aft spoiler using low-cost sheet metal molds. They also developed sponson-mounted skid fins, advanced hydrodynamic sponsons and blunt bows. [1-2]

Paramount to driver safety is the safety cell developed by Ron Jones Marine. Safety cells are also sold as retrofit kits. Figure 1-1 shows a typical safety cell and hydroplane race boat. The safety cells feature flush mounted polycarbonate windows providing 270° visibility and underside emergency rescue hatches.

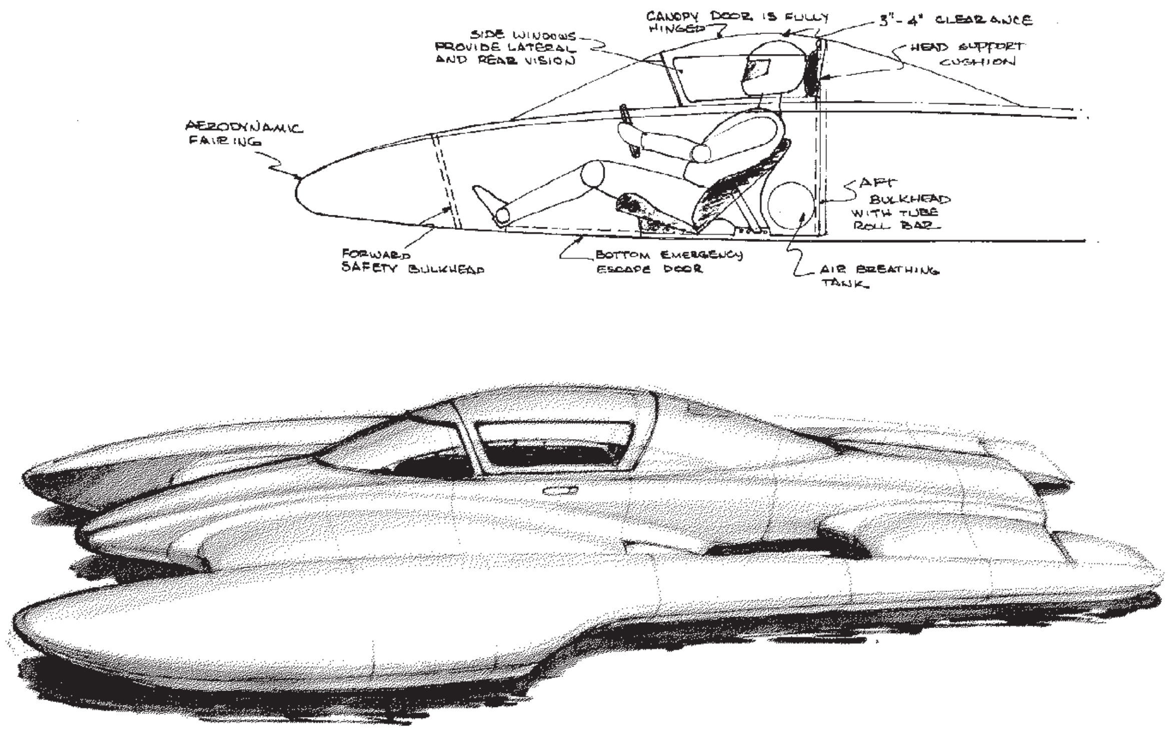


Figure 1-1 Safety Enclosed Driver Capsule from Ron Jones Marine and Rendering of High-Speed Hydroplane Built by with Prepreg Material [Ron Jones Marine]

Racing Sailboats

During the 1970s and 1980s, the American Bureau of Shipping (ABS) reviewed plans for racing yachts. Although this practice is being discontinued, designers continue to use the "ABS Guide for Building and Classing Offshore Racing Yachts" [1-3] for scantling development.

The new *America's Cup Class Rule* specifies a modern, lightweight, fast monohull sloop with characteristics somewhere between an IOR Maxi and an Ultra-Light Displacement Boat (ULDB). [1-4] Figure 1-2 shows a preliminary design developed by Pedrick Yacht Designs in late 1988. The performance of these boats will be highly sensitive to weight, thus, there is a premium on optimization of the structure. The structural section of the rule calls for a thin skin sandwich laminate with minimum skin and core thicknesses and densities, as well as maximum core thickness, fiber densities and cure temperatures. Table 1-1 summarizes the laminate designation of the *America's Cup Class Rule*.

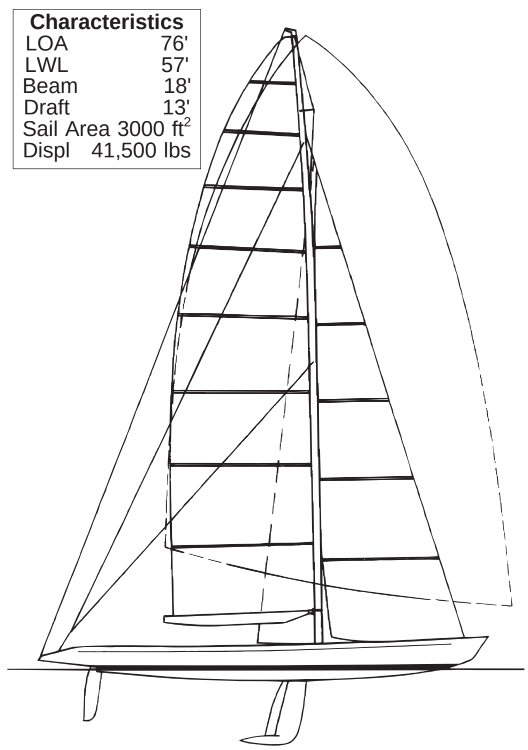


Figure 1-2 Preliminary ACC Design Developed by Pedrick Yacht Designs

Table 1-1 ***America's Cup Class Rule*** **Laminate Requirements [1-6]**

Property	Hull Below LBG Plane Forward of Midships	Rest of Hull Shell	Deck and Cockpits	Units
Minimum Outside Skin Weight	0.594	0.471	0.389	pounds/ft^2
Minimum Inside Skin Weight	0.369	0.287	0.287	
Minimum Core Weight	0.430	0.348	0.123	
Minimum Total Sandwich Weight	1.393	1.106	0.799	
Minimum Single-Skin Weight	2.253	1.638	1.024	
Minimum Outside Skin Thickness	0.083	0.067	0.056	inches
Minimum Inside Skin Thickness	0.052	0.040	0.032	
Minimum Core Thickness	1.151	1.151	0.556	
Maximum Core Thickness	2.025	2.025	1.429	
Minimum Core Density	4.495	3.559	2.684	pounds/ft^3
Minimum Outside Skin Density	84.47	86.22	84.72	
Minimum Inside Skin Density	87.40	86.47	109.25	
Maximum Fiber Modulus	34×10^6			pounds/in^2
Maximum Cure Temperature	203°			°F
Maximum Cure Pressure	0.95 Atmospheres @ STP			

Figure 1-3 1995 America's Cup Winner New Zealand [photo by the author]

Several classes of boats were early pioneers for various construction and production techniques and are presented here as illustrations of the industry's evolutionary process.

Sunfish

The perennial sunfish has served as the introduction to the sport for many sailors. The simplicity of the lanteen rig and the board-like hull make the craft ideal for beaching and cartopping. Alcort has produced over 250,000 of them since their inception in 1952. The basically two-piece construction incorporates a hard chine hull to provide inherent structural stiffening.

Boston Whaler

Boston Whaler has manufactured a line of outboard runabouts since the early 1960s. The 13 foot tri-hull has been in production since 1960, with over 70,000 built. The greatest selling feature of all their boats is the unsinkable hull construction resulting from a thick foam sandwich construction. Hull and deck sections are sprayed-up with ortho-polyester resin to a 33% glass content in massive steel molds before injected with an expanding urethane foam. The 1¾ to 2½ inch core provides significant strength to the hull, enabling the skins to be fairly thin and light. Another interesting component on the Whalers is the seat reinforcement, which is made of fiberglass reinforced Zytel®, a thermoplastic resin.

Block Island 40

The Block Island 40 is a 40 foot yawl that was designed by William Tripp and built by the American Boat Building Co. in the late 1950s and early 1960s. At the time of construction, the boat was the largest offshore sailboat built of fiberglass. Intended for transatlantic crossings, a very conservative approach was taken to scantling determination. To determine the damage tolerance of a hull test section, a curved panel was repeatedly run over with the designer's car. The mat/woven roving lay-up proved adequate for this trial as well as many years of in-service performance. At least one of these craft is currently enjoying a second racing career thanks to some keel and rig modifications.

Laser International

Starting in 1973, Laser used a production line vacuum bag system to install PVC foam core (Airex®, Clarke® and Core-Cell®). The same system has been used for the construction of over 135,000 boats. [1-7]

Laser International invested $1.5 million in the development and tooling of a new, bigger boat, the 28 foot Farr Design Group Laser 28. The Laser 28 has a PVC foam core deck with aramid fabric inner and outer skins. A dry sandwich mold is injected with a slow curing liquid resin through multiple entry ports, starting at the bottom of the mold and working upward. [1-8]

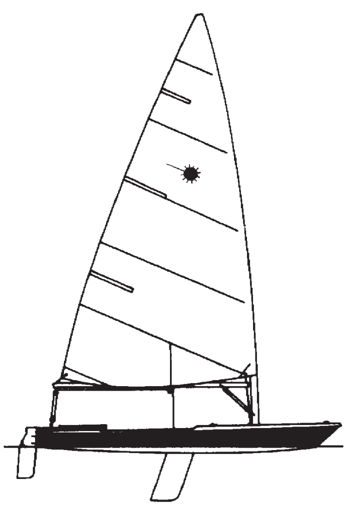


Figure 1-4 14 Foot Laser Sailboat [Laser International]

J/24

The J/24 fractional rigged sloop has been manufactured since 1977 at the rate of about 500 per year. The vessel has truly become a universally accepted "one-design" class allowing sailors to race on a boat-for-boat basis without regard for handicap allowances. Part of the fleet's success is due to the manufacturer's marketing skills and part is due to the boat's all-around good performance. The hull construction is cored with "Contourkore" end-grain balsa. Its builder, TPI, manufactures J/Boats along with Freedoms, Rampages and Aldens (see page 7 for more information on TPI).

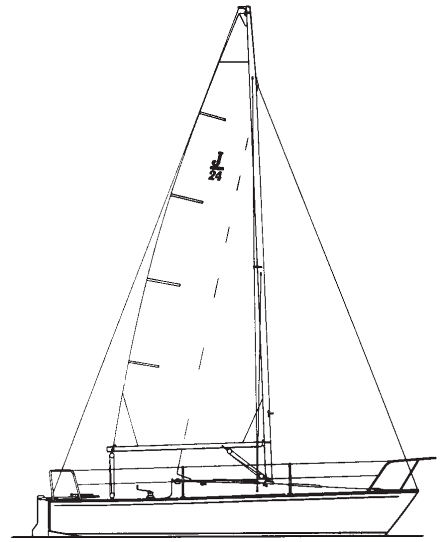


Figure 1-5 International J/24 Sailboat [J /Boats]

IMP

IMP is a 40 foot custom ocean racing sloop that represented the U.S. in the Admiral's Cup in 1977 and 1979. She was probably the most successful design of Ron Holland, with much of her performance attributable to sophisticated construction techniques. The hull and deck are of sandwich construction using a balsa core and unidirectional reinforcements in vinyl ester resin. Primary rig and keel loads are anchored to an aluminum box and tube frame system, which in turn is bonded to the hull. In this way, FRP hull scantlings are determined primarily to resist hydrodynamic forces. The resulting hybrid structure is extremely light and stiff. The one-off construction utilized a male mold.

Admiral

Admiral Marine was founded in Seattle about 50 years ago by Earle Wakefield. His son, Daryl, moved the company to Port Townsend in 1979 and built their first fiberglass boat in 1981. The launch of the 161-foot ***Evviva*** in 1993 thrust the company into the forefront of custom FRP construction. ***Evviva*** is the largest fully foam-cored boat built in North America. Kevlar® and carbon reinforcements are used where needed, as are Nomex® honeycomb cores for interior furniture.

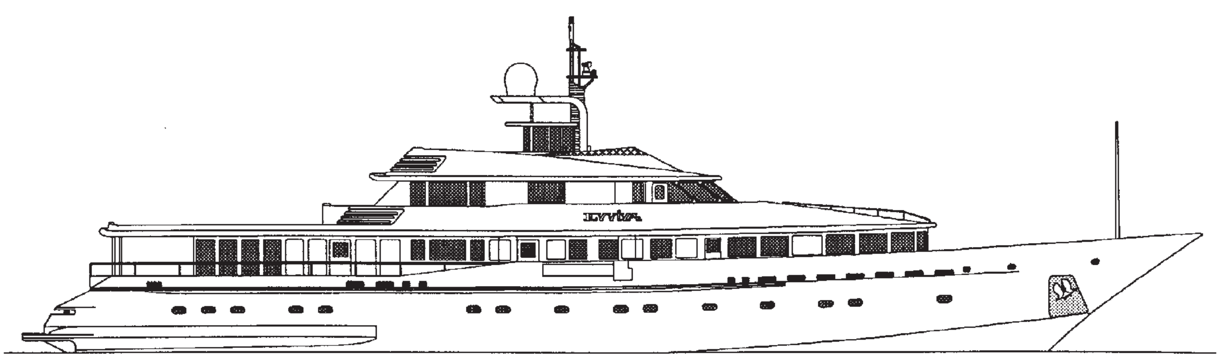


Figure 1-6 161' Motoryacht *Evviva* Built by Admiral Marine [Admiral]

Evviva's light ship displacement of 420,000 pounds permits a cruising speed of 25 knots and top end speed of 30.6 knots with two MTU 16V396's. The owner wanted a gel coat finish throughout, which required building the boat from over 180 female molds. Molded components included tanks, air plenums, genset exhaust ducts, and freezers.

Bertram

Bertram Yachts has built cruiser and sport fisherman type powerboats since 1962. Their longevity in the business is in part attributable to sound construction and some innovative production techniques. All interior joinery and structural elements are laminated to a steel jig, which positions these elements for precise attachment to the hull. A combination of mat, woven roving, knitted reinforcements and carbon fibers are used during the hand lay-up of a Bertram.

Christensen

Christensen has been building a line of semi-custom motor yachts over 100 feet long, as illustrated in Figure 1-7 since 1978. The hulls are Airex® foam cored using a vacuum assist process. All yachts are built to ABS classification and inspection standards. The yard has built over 20 yachts using the expandable mold technique popular in the Pacific Northwest.

Christensen claims to have the largest in-house engineering staff of any U.S. yacht manufacturer. Their 92,000 square-foot, climate-controlled facility has six bays to work on vessels at various stages of completion. The company is currently concentrating on yachts in the 120-150 foot range.

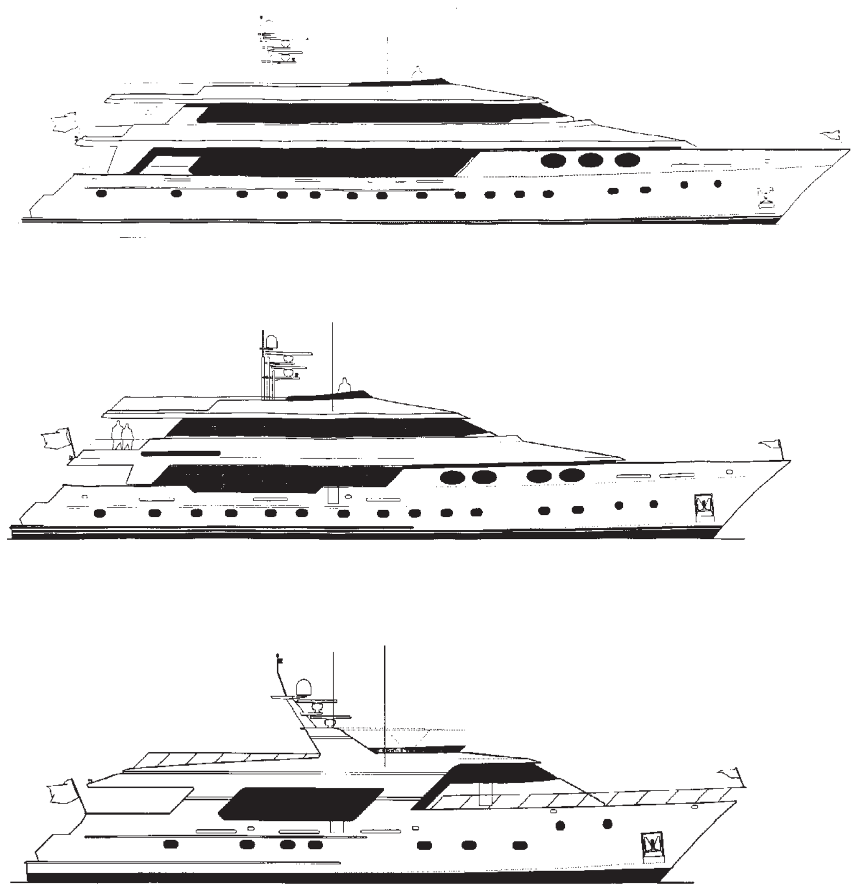


Figure 1-7 150', 135', and 107' Motor Yachts Produced by Christensen Motor Yacht Corporation [Christensen]

Delta Marine

Delta Marine built its reputation on building strong FRP fishing trawlers for the Pacific Northwest. Unfortunately, the fishing industry has dropped off and the FRP boats show little wear and don't require replacement. Delta has found a niche for their seaworthy designs with yacht owners interested in going around the world.

Examples of their 131-foot and 105-foot semi-displacement yachts are shown in Figure 1-8. They currently have a 150-foot design under construction. Charter vessels for sightseeing and fishing are also built using single-skin hull construction. Hull sides, decks and deckhouses are balsa cored.

Delta employs up to 200 skilled craftsman and an engineering staff of 10 to build on a semi-custom basis using adjustable female hull molds. Characteristic of Delta-built motor yachts is a bulbous bow, more often found on large ships to improve seakeeping and fuel economy.

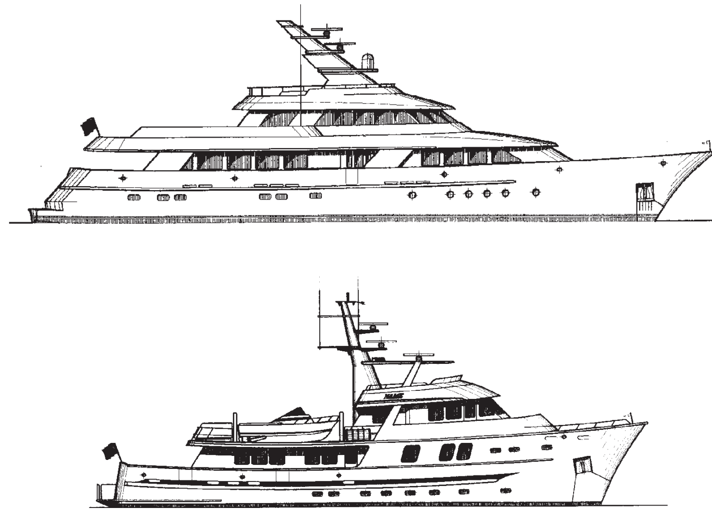


Figure 1-8 131' Semi-Displacement Motoryacht and 105' Deep-Sea Motoryacht are Typical of Designs Offered by Delta Marine [Delta]

Eric Goetz

Eric Goetz began building custom boats in Bristol, RI in 1975 working with the Gougeon Brothers WEST system. In 1995, Goetz built all of the defending America's Cup boats using prepreg technology. Low temperature epoxy prepregs are vacuum consolidated and cured in a portable oven. Nomex® and aluminum honeycomb cores are used with this process, as are glass, carbon and Kevlar® reinforcements.

Of the 80 or so boats that Goetz has built, most are racing or cruising sailboats designed to go fast. He also has applied his skills at an offshore racing powerboat and some specialized military projects. Goetz believes that prepreg technology can be competitive with high-end wet lay-up methods for semi-custom yachts. Goetz Marine Technology (GMT) is a spin-off company that builds carbon fiber/epoxy masts, rudders and specialized hardware.

TPI

TPI is the latest boatbuilding enterprise of Everett Pearson, who built his first boat over forty years ago and has built 15,000 since. In 1959, Pearson began building the 28-foot, Carl Alberg designed Triton. This design was the first true production FRP sailboat and many are still sailing.

Today, TPI builds sailboats for five different companies, including J-Boats, and manufactures windmill blades, people movers and swim spas. TPI was an early partner in the development of the SCRIMP resin infusion process. Except for their class boats, such as the J-24, all TPI's construction utilizes this process that involves "dry" lay-up of reinforcements and infusion of resin with a closed, vacuum process. TPI makes extensive use of research & development efforts to improve materials and processes involved with construction of large composite structures for a variety of recreational and industrial applications.

Trident

Trident Shipworks in Tampa, FL handles a wide range of projects on a custom basis. Although recently founded (1992), the executive staff of Trident has participated in the fabrication of over 100 yachts in excess of 60 feet. Gary Carlin brings the background of race yacht construction from Kiwi Boats. Most designs are built with foam core construction over male jigs. Hulls are typically built with vinyl ester or epoxy resins. Trident has capabilities to post cure parts in excess of 100 feet. Some yachts recently completed include a 104' Tripp-designed fast cruising sailboat; a 115' Hood-designed shallow draft cruiser (see Figure 1-9); a 105' waterjet powered S&S motoryacht; and a 120' Jack Hargrave long-rang motoryacht.

Figure 1-9 150-foot Omohundro carbon Fiber/Epoxy Mast for 115' Ted Hood Designed Shallow Draft Sailing Yacht Built by Trident Shipworks [photo by the author]

Westport Shipyard

Westport Shipyard was established in 1964 initially to supply services to their local commercial fleet. After the first few years, the shipyard began to construct commercial boats which are now in use throughout the West Coast, Alaska, Hawaii, and American Somoa. In 1977, the shipyard was sold to its present owners, Rick and Randy Rust. Up until 1977, the shipyard had specialized in producing commercial salmon trollers and crab boats in the 36 to 40 foot range, as well as commercial charter vessels in the 53 to 62 foot range, all built with fiberglass. After 1977, Westport began to build much larger commercial and passenger boats and larger pleasure yachts. This trend continues today, with most vessels being in the 80 to 115 foot size range. Westport claims to have built more large (80 foot through 128 foot) fiberglass hulls than any other builder in the United States.

The Westport Shipyard developed their variable size mold concept when they found that a 70 foot by 20 foot mold was constantly being modified to fabricate vessels of slightly different dimensions. A single bow section is joined to a series of shapable panels that measure up to 10 feet by 48 feet. The panels are used to define the developable sections of the hull. Since 1983, over 50 hulls have been produced using this technique. Expensive individual hull tooling is eliminated, thus making custom construction competitive with aluminum. A layer of mat and four woven rovings is layed-up wet with impregnator machines.

Westport's Randy Rust has streamlined the number of man-hours required to build cored, 100-foot hulls. These Jack Sarin hull forms are used for both motoryachts, such as the stylish 106-foot ***Westship Lady***, and commercial vessels, such as excursion boats and high-speed ferries.

Canoes and Kayaks

Competition canoes and kayaks employ advanced composites because of the better performance gained from lighter weight, increased stiffness and superior impact resistance. Aramid fiber reinforced composites have been very successful, and new fiber technologies using polyethylene fiber reinforcement are now being attempted. The boat that won the U.S. National Kayak and Canoe Racing Marathon was constructed with a new high molecular weight polyethylene fiber and was 40% lighter than the identical boat made of aramid fiber. [1-1]

Evolution of Recreational Boat Construction Techniques

From the 1950s to the 1990s, advances in materials and fabrication techniques used in the pleasure craft industry have helped to reduce production costs and improve product quality. Although every boat builder employs unique production procedures that they feel are proprietary, general industry trends can be traced over time, as illustrated in Figure 1-10.

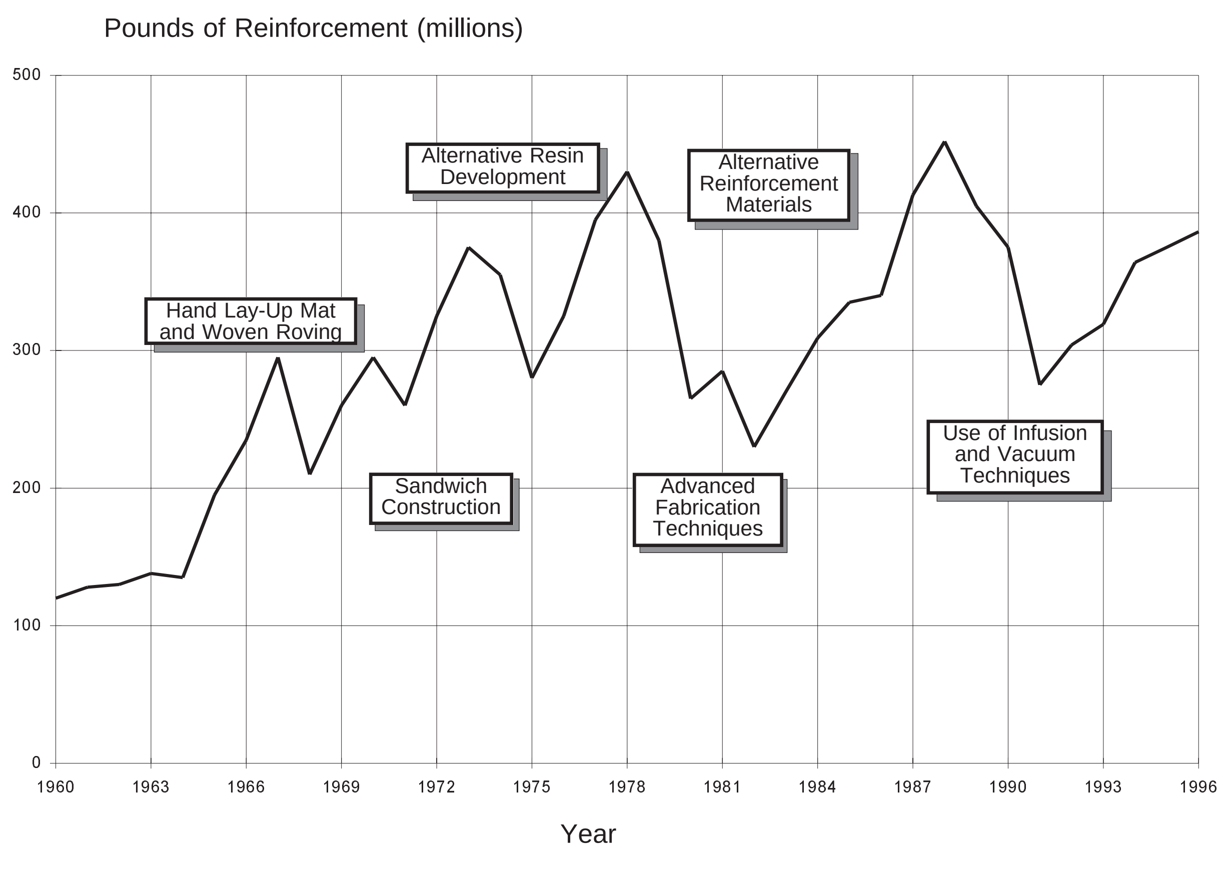


Figure 1-10 Annual Shipment of Reinforced Thermoset and Thermoplastic Resin Composites for the Marine Industry with Associated Construction Developments. [Data Source: SPI Composites Institute (1960-1973 Extrapolated from Overall Data)]

Single-Skin Construction

Early fiberglass boat building produced single-skin structures with stiffeners to maintain reasonable panel sizes. Smaller structures used isotropic (equal strength in x and y directions) chopped strand mat layed-up manually or with a chopper gun. As strength requirements increased, fiberglass cloth and woven roving were integrated into the laminate. An ortho-polyester resin, applied with rollers, was almost universally accepted as the matrix material of choice.

Sandwich Construction

In the early 1970s, designers realized that increasingly stiffer and lighter structures could be achieved if a sandwich construction technique was used. By laminating an inner and outer skin to a low density core, reinforcements are located at a greater distance from the panel's neutral axis. These structures perform exceptionally well when subjected to bending loads produced by hydrodynamic forces. Linear and cross-linked PVC foam and end-grain balsa have evolved as the primary core materials.

Resin Development

General purpose ortho-polyester laminating resins still prevail throughout the boating industry due to their low cost and ease of use. However, boat builders of custom and higher-end craft have used a variety of other resins that exhibit better performance characteristics. Epoxy resins have long been known to have better strength properties than polyesters. Their higher cost has limited use to only the most specialized of applications. Iso-polyester resin has been shown to resist blistering better than ortho-polyester resin and some manufacturers have switched to this entirely or for use as a barrier coat. Vinyl ester resin has performance properties somewhere between polyester and epoxy and has recently been examined for its excellent blister resistance. Cost is greater than polyester but less than epoxy.

Unidirectional and Stitched Fabric Reinforcement

The boating industry was not truly able to take advantage of the directional strength properties associated with fiberglass until unidirectional and stitched fabric reinforcements became available. Woven reinforcements, such as cloth or woven roving, have the disadvantage of “pre-buckling” the fibers, which greatly reduces in-plane strength properties. Unidirectional reinforcements and stitched fabrics that are actually layers of unidirectionals offer superior characteristics in the direction coincident with the fiber axis. Pure unidirectionals are very effective in longitudinal strength members such as stringers or along hull centerlines. The most popular of the knitted fabrics is the 45^o by 45^o knit, which exhibits superior shear strength and is used to strengthen hulls torsionally and to tape-in secondary structure.

Advanced Fabrication Techniques

Spray-up with chopper guns and hand lay-up with rollers are the standard production techniques that have endured for 40 years. In an effort to improve the quality of laminated components, some shops have adapted techniques to minimize voids and increase fiber ratios. One technique involves placing vacuum bags with bleeder holes over the laminate during the curing process. This has the effect of applying uniform pressure to the skin and drawing out any excess resin or entrapped air. Another technique used to achieve consistent laminates involves using a mechanical impregnator, which can produce 55% fiber ratios.

Alternate Reinforcement Materials

The field of composites gives the designer the freedom to use various different reinforcement materials to improve structural performance over fiberglass. Carbon and aramid fibers have evolved as two high strength alternatives in the marine industry. Each material has its own advantages and disadvantages, which will be treated in a later chapter. Suffice it to say that both are significantly more expensive than fiberglass but have created another dimension of options with regards to laminate design. Some low-cost reinforcement materials that have emerged lately include polyester and polypropylene. These materials combine moderate strength properties with high strain-to-failure characteristics.

Infusion Methods

In an effort to reduce styrene emissions and improve the overall quality of laminates, some builders are using or experimenting with resin infusion techniques. These processes use traditional female molds, but allow the fabricator to construct a laminate with dry reinforcement material called preforms. Similar to vacuum methods, sealant bags are applied and resin is distributed through ports using various mediums. In general, fiber content of laminates made with infusion methods is increased. Various infusion methods are described in Chapter Five.

Commercial Marine Industry

The use of fiberglass construction in the commercial marine industry has flourished over time for a number of different reasons. Initially, long-term durability and favorable fabrication economics were the impetus for using FRP. More recently, improved vessel performance through weight reduction has encouraged its use. Since the early 1960s, a key factor that makes FRP construction attractive is the reduction of labor costs when multiple vessels are fabricated from the same mold. Various sectors of the commercial market will be presented via examples of craft and their fabricators. Activity levels have traditionally been driven by the economic factors that influence the vessel's use, rather than the overall success of the vessels themselves.

Utility Vessels

Boats built for utility service are usually modifications of existing recreational or patrol boat hulls. Laminate schedules may be increased or additional equipment added, depending upon the type of service. Local and national law enforcement agencies, including natural resource management organizations, compromise the largest sector of utility boat users. Other mission profiles, including pilotage, fire-fighting and launch service, have proven to be suitable applications of FRP construction. To make production of a given hull form economically attractive, manufacturers will typically offer a number of different topside configurations for each hull.

Boston Whaler

Using similar construction methods outlined for their recreational craft, Boston Whaler typically adds some thickness to the skins of their commercial boats. Hulls 17 feet and under are of tri-hull configuration, while the boats above 18 feet are a modified “deep-V” with a deadrise angle of 18 degrees. The majority of boats configured for commercial service are for either the Navy, Coast Guard or Army Corps of Engineers. Their durability and proven record make them in demand among local agencies.

LeComte

LeComte Holland BV manufactured versatile FRP landing craft using vacuum-assisted injection molding. S-glass, carbon and aramid fibers were used with polyester resin. The entire hull is molded in one piece using male and female molds via the resin transfer molding (RTM) process.

LeComte introduced a new type of rigid hull, inflatable rescue boat. The “deep-V” hull is made by RTM with hybrid fibers, achieving a 25% weight savings over conventional methods. Boat speeds are in excess of 25 knots. [1-9]

Textron Marine Systems

Textron Marine Systems has long been involved with the development of air cushion and surface effect ships for the government. In 1988, the company implemented an R & D program to design and build a small air cushion vehicle with a minimal payload of 1200 pounds. The result is a line of vessels that range in size from 24 to 52 feet that are fabricated from shaped solid foam block, which is covered with GRP skins. The volume of foam gives the added value of vessel unsinkability. Shell Offshore Inc. has taken delivery of a 24 foot version for use near the mouth of the Mississippi River. Figure 1-11 shows a typical cargo configuration of the type of vessel delivered to Shell.

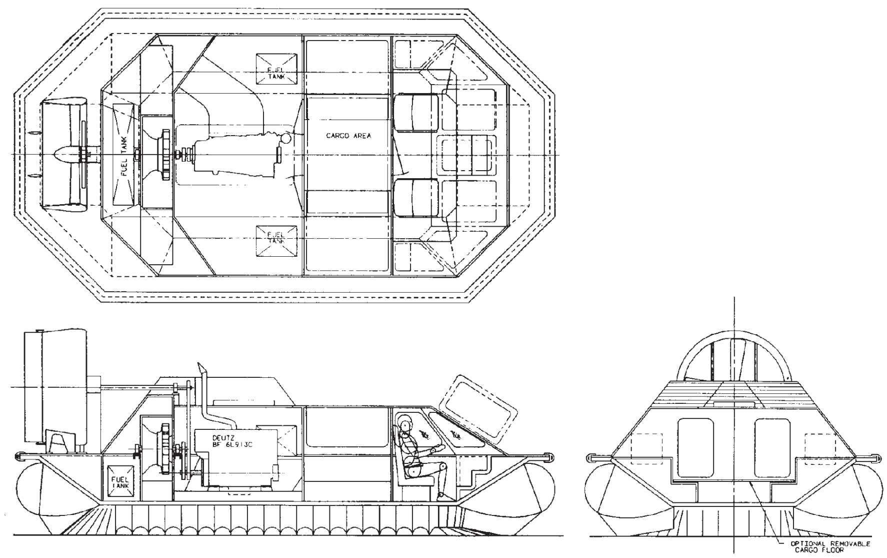


Figure 1-11 Cargo Configuration for Textron Marine's Utility Air Cushion Vehicle - Model 1200 [Textron Marine]

Passenger Ferries

Blount Marine

Blount Marine has developed a proprietary construction process they call Hi-Tech© that involves the application of rigid polyurethane foam over an aluminum stiffening structure. A fleet of these vessels have been constructed for New York City commuter runs.

Karlskronavarvet, AB

Karlskronavarvet, AB in Karlskrona, Sweden, is among several European shipyards that build passenger and automobile ferries. The Surface Effect Ship (SES), ***Jet Rider*** is a high speed passenger ferry designed and fabricated by Karlskronavarvet in 1986 for service in Norway. The ***SES Jet Rider*** is an air cushioned vehicle structured entirely of GRP sandwich. The SES configuration resembles a traditional catamaran except that the hulls are much narrower. The bow and stern are fitted with flexible seals that work in conjunction with the hulls to trap the air cushion. The air cushion carries about 85% of the total weight of the ship with the remaining 15% supported by the hulls. The design consists of a low density PVC cellular plastic core material with closed, non-water-absorbing cells, covered with a face material of glass fiber reinforced polyester plastic. The complete hull, superstructure and foundation for the main engines and gears are also built of GRP sandwich. Tanks for fuel and water are made of hull-integrated sandwich panels. The speed under full load is 42 knots (full load includes 244 passengers and payload totaling 27 metric tons). [1-10]

Figure 1-12 Finnyard's ***Stena HSS*** (High Speed Sea Service) 124 Meter Ferry Features the Use of Composites for Bulbous Bow Sections, as well as for Stacks, Stairwells, A/C Spaces and Interior Furniture [Fast Ferry International]

Air Ride Craft

Don Burg has patented a surface effect ship that utilizes a tri-hull configuration and has developed the concept for the passenger ferry market. Although the 109 foot version is constructed of aluminum, the 84 and 87 foot counterparts are constructed from Airex®-cored fiberglass to ABS specifications. The FRP vessels are constructed in Hong Kong by Cheoy Lee Shipyards, a pioneer in Far East FRP construction. Also to their credit is a 130 foot, twin-screw motor yacht that was constructed in 1976.

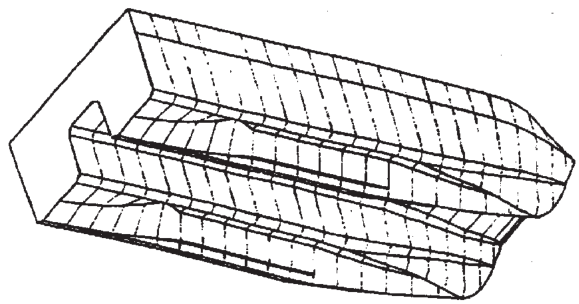


Figure 1-13 Isometric View of the Patented Air Ride SeaCoaster Hull Form Shows Complex Shapes Ideally Suited to Composite Construction [Air Ride Brochure]

Market Overview

Conventional ferries are being replaced by fast ferries, due to improved economic conditions, increased leisure time, demands for faster travel, and more comfort and safety, air congestion, reduced pollution, and higher incomes. To date, composite construction was been utilized more extensively by overseas builders of commercial vessels.

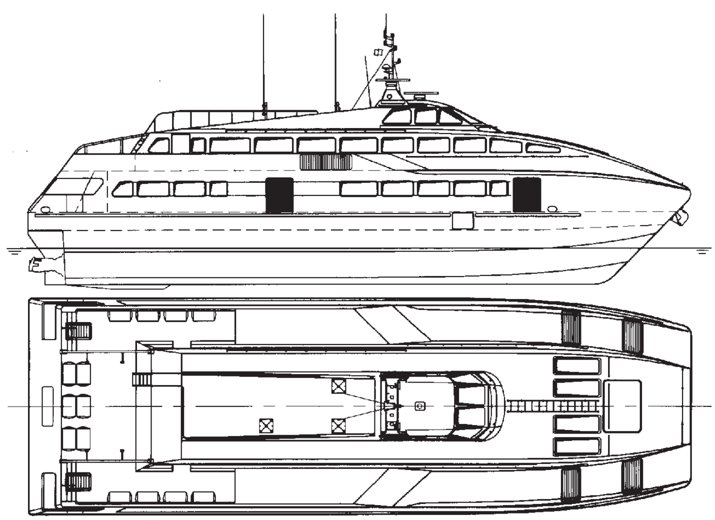


Figure 1-14 Samsung Built This 37-meter SES Designed by Nigel Gee and Associates using a Kevlar® Hybrid Reinforcement for the Hull [DuPont, Oct 1993, **Marine Link**]

Commercial Ship Construction

In 1971, the Ship Structure Committee published a detailed report entitled “Feasibility Study of Glass Reinforced Plastic Cargo Ship” prepared by Robert Scott and John Sommella of Gibbs & Cox [1-11]. A 470 foot, dry/bulk cargo vessel was chosen for evaluation whereby engineering and economic factors were considered. It would be instructive to present some of the conclusions of that study at this time.

- The general conclusion was that the design and fabrication of a large GRP cargo ship was shown to be totally within the present state-of-the-art, but the long-term durability of the structure was questionable;
- The most favorable laminate studied was a woven-roving/unidirectional composite, which proved 43% lighter than steel but had 20% of the stiffness;
- GRP structures for large ships currently can't meet present U.S. Coast Guard fire regulations and significant economic incentive would be necessary to pursue variants.;
- Cost analyses indicate unfavorable required freight rates for GRP versus steel construction in all but a few of the sensitivity studies.;
- Major structural elements such as deckhouses, hatch covers, king posts and bow modules appear to be very well suited for GRP construction.; and
- Commercial vessels of the 150-250 foot size appear to be more promising than the vessels studied and deserve further investigation.

Applications for Advanced Composites on Large Ships

There are numerous non load-bearing applications of FRP materials in commercial ships where either corrosion resistance, weight or complex geometry justified the departure from conventional materials. As an example, in the early 1980s, Farrell Lines used FRP false stacks in their C10 vessels that weighed over 30 tons. Also, piping for ballast and other applications is commonly made from FRP tubing.

Italian shipbuilder Fincantieri has used composites for cruise liner stacks, such as the 10 x 16 x 40-foot funnels for Costa Crociere Line that represented a 50% weight and 20% cost savings over aluminum and stainless steel structures they replaced. Fincantieri is also investigating FRP deckhouses in collaboration with classification societies. [1-12]

Advanced composite materials on large ships have the potential to reduce fabrication and maintenance costs, enhance styling, reduce outfit weight and increase reliability. George Wilhelmi, of the Navy's NSWC, Carderock Research Center in Annapolis summarized potential ship applications for composite materials as follows:

Structural	Machinery	Functional
Topside Superstructure	Piping	Shafting Overwraps
Masts	Pumps	Life Rails/Lines
Stacks	Valves	Handrails
Foundations	Heat Exchangers	Bunks/Chairs/Lockers
Doors	Strainers	Tables/Worktops
Hatches	Ventilation Ducting	Insulation
Liferails	Fans, Blowers	Nonstructural Partitions
Stanchions	Weather Intakes	Seachest Strainers
Fairings	Propulsion Shafting	Deck Grating
Bulkheads	Tanks	Stair Treads
Propellers	Gear Cases	Grid Guards
Control Surfaces	Diesel Engines	Showers/Urinals
Tanks	Electrical Enclosures	Wash Basins
Ladders	Motor Housings	Water Closets
Gratings	Condenser Shells	Mast Stays/Lines

Current regulatory restrictions limit the use of composite materials on large passenger ships to nonstructural applications. This is the result of IMO and USCG requirements for non-combustibility. ASTM test E1317-90 (IMO LIFT) is designed to measure flammability of marine surface finishes used on non combustible substrates. These include deck surfacing materials, bulkhead and ceiling veneers and paint treatments. Systems that qualify for testing to this standard include nonstructural bulkheads, doors and furniture.

Momentum exists to increase the use of composite materials, especially for above deck structures where weight and styling are major drivers. Stylized deckhouse structure and stacks are likely candidates for composites, as regulations permit this.

Commercial Deep Sea Submersibles

Foam cored laminates are routinely being used as buoyancy materials in commercial submersibles. The Continental Shelf Institute of Norway has developed an unmanned submersible called the ***Snurre***, with an operating depth of 1,500 feet, that uses high crush point closed cell PVC foam material for buoyancy. From 1977 to 1984 the ***Snurre*** operated successfully for over 2,000 hours in the North Sea. The French manned submersible, ***Nautile***, recently visited the sea floor at the site of the ***Titanic*****.** The ***Nautile*** is a manned submersible with operating depths of 20,000 feet and uses high crush point foam for buoyancy and FRP materials for non-pressure skins and fairings. The oil industry is making use of a submersible named ***David*** that not only utilizes foam for buoyancy, but uses the foam in a sandwich configuration to act as the pressure vessel. The use of composites in the ***David***'s hull allowed the engineers to design specialized geometries that are needed to make effective repairs in the offshore environment. [1-1]

Slingsby Engineering Limited designed and developed a third-generation remotely operated vehicle called ***Solo*** for a variety of inspection and maintenance functions in the offshore industry. ***Solo*** carries a comprehensive array of sophisticated equipment and is designed to operate at a depth of 5,000 feet under a hydrostatic pressure of 2 ksi. The pressure hull, chassis and fairings are constructed of glass fiber woven roving. [1-13]

A prototype civilian submarine has been built in Italy for offshore work. The design consists of an unpressurized, aramid-epoxy outer hull that offers a better combination of low weight with improved stiffness and impact toughness. The operational range at 12 knots has been extended by two hours over the range of a glass hull. [1-14]

Navigational Aids

Steel buoys in the North Sea are being progressively replaced with plastic buoys due to increasing concern of damage to vessels. Balmoral Glassfibre produces a complete line of buoys and a light tower made of GRP that can withstand winds to 125 mph. Anchor mooring buoys supplied to the Egyptian offshore oil industry are believed to be the largest GRP buoys ever produced. These 13 foot diameter, 16.5 ton reserve buoyancy moorings are used to anchor tankers of up to 330,600 ton capacity. [1-15]

Offshore Engineering

At a September, 1990 conference sponsored by the Ship Structure Committee and the National Academy of Sciences entitled "*The Use of Composite Materials in Load-Bearing Marine Structures*," Jerry Williams of Conoco reported that composites show the potential for improved corrosion resistance and weight reduction for numerous applications in offshore oil recovery structures. The Tension Leg Platform (TLP) is a leading candidate for oil and gas production facilities in deep water. Figure 1-15 shows how these structures react to wave energy versus fixed-leg platforms. TLP's are extremely weight sensitive and could benefit from composite tendons and floating structure. Williams also proposes the use of pultruded composite piping similar to the configurations shown in Figure 1-16. The piping needs to resist 1000 psi internal loads, have good longitudinal strength and stiffness (see 0° graphite), and must be able to roll on a large spool for use with cable laying ships. [1-16]

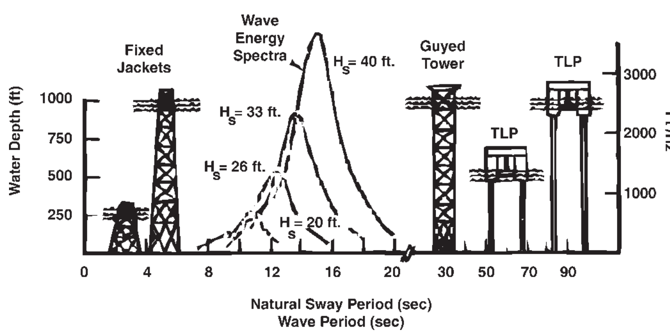


Figure 1-15 Platform Natural Sway Period Relative to Sea State Energy [Jerry Williams, Conoco]

Composite materials are already being used in offshore hydrocarbon production because of their weight, resistance to corrosion and good mechanical properties. One proposed new use for composites is for submarine pipelines, with circumferential carbon fibers providing resistance to external pressure and longitudinal glass fibers providing lengthwise flexibility. [1-9]

Another application for deep sea composites is drilling risers for use at great water depths. Composites would significantly reduce the dynamic stress and increase either the working depth or the safety of deep water drilling. Fifty foot lines made from carbon and glass fibers, with a burst pressure of 25 ksi, have been effectively subjected to three successive drilling sessions to 10 ksi from the North Sea rig ***Pentagone 84***. [1-9]

The National Institute of Science and Technology recently awarded the Composite Production Risers Joint Venture $3.6 million from their Advanced Technology Program to develop a composites-based technology suitable for production risers and other components of offshore oil facilities that will enable access to the reserves found in deepwater tracts of the Gulf of Mexico. Westinghouse Electric and five partners were also granted an award under this program to study test processes for composites. The Spoolable Composite Joint Venture received a $2.5 million award to study the tubular composite material described above.

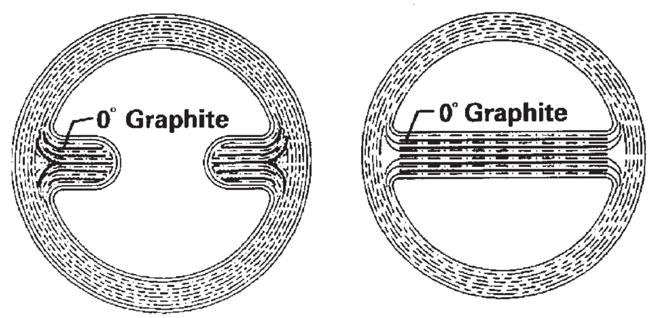


Figure 1-16 Two Proposed Composite Riser Geometries Utilizing E-Glass for the Bodies of the Tubes [Jerry Williams, Conoco, SSC/NAS Sep 1990 conference]

Platform Firewater Mains

Specialty Plastics of Baton Rouge, LA has recently installed Fiberbond 20-FW-HV piping systems and connectors for fire fighting systems on three oil production platforms in the Gulf of Mexico. Rick Lea of Specialty Plastics notes that the composite piping system is price competitive with schedule 80 carbon steel pipe and one-third the cost of 90/10 copper-nickel pipe. The composite pipes weigh one-fifth what the steel weighs, making handling and installation much easier. Because no welding is required, installation is also simplified in this often harsh environment. Superior corrosion resistance reduces maintenance time for this mission critical system. [1-17] Specialty installed a system that was fire hardened with PPG's PittChar and hard insulation in quantities to meet 30 minute endurance tests (IMO level 3) on the ***Shell MARS*** tension leg platform.

Piling Forms and Jackets

Downs Fiberglass, Inc. of Alexandria, VA has developed a line of forms and jackets for use in the building and restoration of bridge columns. The "tidal zone" of maritime structures is known to endure the most severe erosion effects and traditionally is the initial area requiring restoration. Common practice involves the use of a pourable epoxy to encapsulate this portion of decaying piles. Repairs using the jacketing system can also be accomplished underwater.

The forms shown in Figure 1-17 are lightweight permanent forms with specially treated inner surfaces to enhance bonding characteristics. The basic jacket material is E-glass mat and woven roving in a polyester resin matrix.

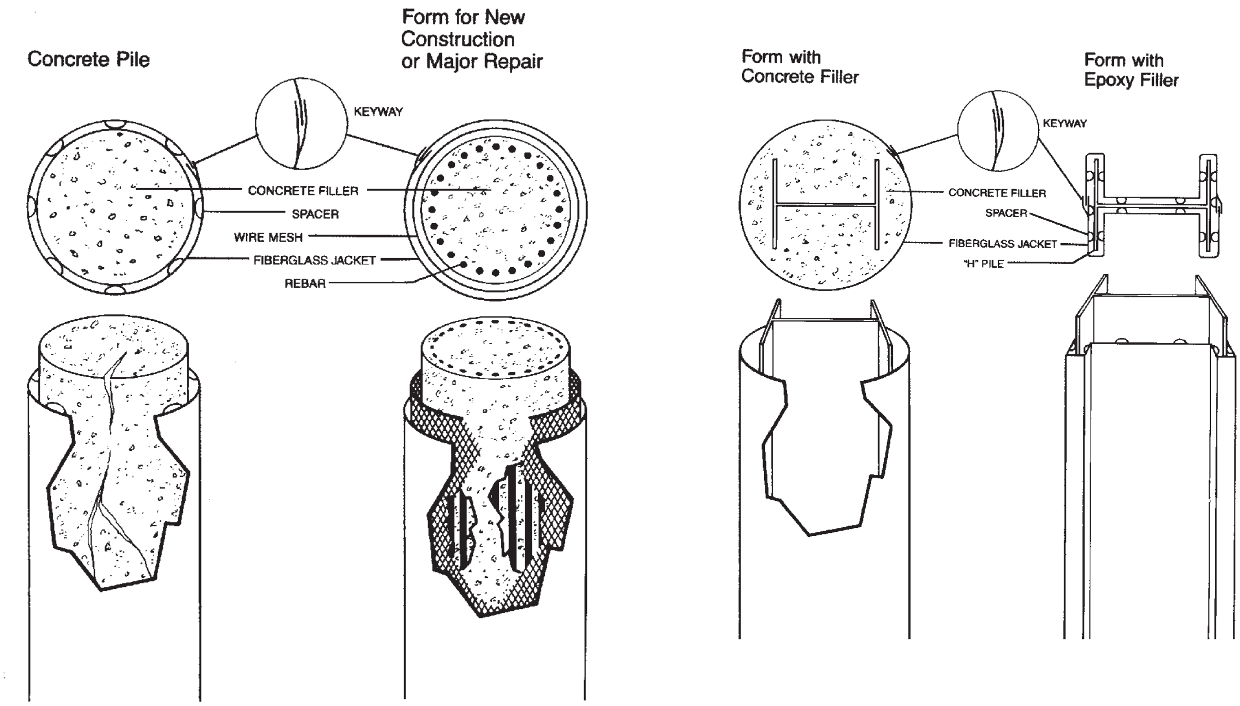


Figure 1-17 Fiberglass Forms and Jackets for Pylon Erosion Restoration [Downes]

Seaward International

The Seapile™ composite marine piling is a new piling for dock construction introduced by Seaward International, Inc. Made from recycled plastic and drawing upon technology especially developed for this application, the Seapile™ offers the dock designer and facilities manager an alternative to traditional creosoted timber piles (see Figure 1-18). The new pilings are impervious to marine borers, made from recycled materials, are recyclable, and are covered by a tough outer skin.

Seapile™ is manufactured in a continuous process, so one-piece pilings can be made in virtually any length. The plastic compound is made of Duralin™ plastic, a matrix composed of 100% recycled resin and designed by Seaward chemists and engineers for its strength and ability to bond with the structural elements of the pile. It is also resistant to ultraviolet light, chipping and spalling and is impervious to marine borers. About 240 one-gallon milk jugs go into a linear foot of Seapile™. The structural elements that help to form the piling can be either steel or fiberglass. When reinforced with fiberglass, the Seapile™ exhibits a nonmagnetic signature and is one hundred percent recyclable. [1-18]

Figure 1-18 Seapile™ Installation as Replacement for Adjacent Timber Pile [Seaward]

First year customers include the Navy, the ports of Los Angeles and New York, the Army Corps of Engineers, and the Coast Guard. Seaward also produces a square cross section, suitable for use as dock structural members. Future applications include railroad ties and telephone poles. [1-19]

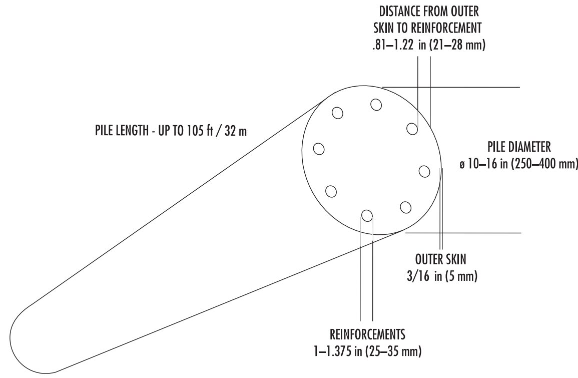


Figure 1-19 Seapile™ Composite Marine Piling [Seaward]

Composite Rebar

Marshall Industries has introduced a line of concrete reinforcing rod (rebar) products built with E-glass, carbon or aramid fibers. The rebars are produced with a urethane-modified vinyl ester resin from Shell. These products are designed to replace steel rebar that traditionally is coated with epoxy to prevent corrosion. The composite rebar is lighter than steel, and has a thermal expansion coefficient similar to concrete. [1-20]

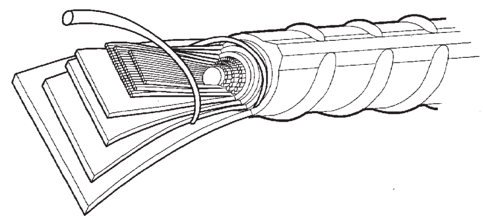


Figure 1-20 C-BAR™ Composite Reinforcing Rod [Marshall Industries]

Navy Advanced Waterfront Technology

Over 75% of the Navy's waterfront structures are over 40 years old, with a repair and modernization budget of $350 million annually. [1-21] The Navy is studying the use of FRP as an alternative to preventing steel corrosion in waterfront reinforced concrete structures. The Naval Facilities Engineering Service Center (NFESC) has constructed a 150 ft. reinforced concrete pier in Port Hueneme, CA. This pier will be used as a test bed for advanced waterfront technologies, in particular for the evaluation of composites in waterfront applications. This is a joint project in coordination with the U.S. Army Corps of Engineers, the South Dakota School of Mines and Technology, and the Composites Institute.

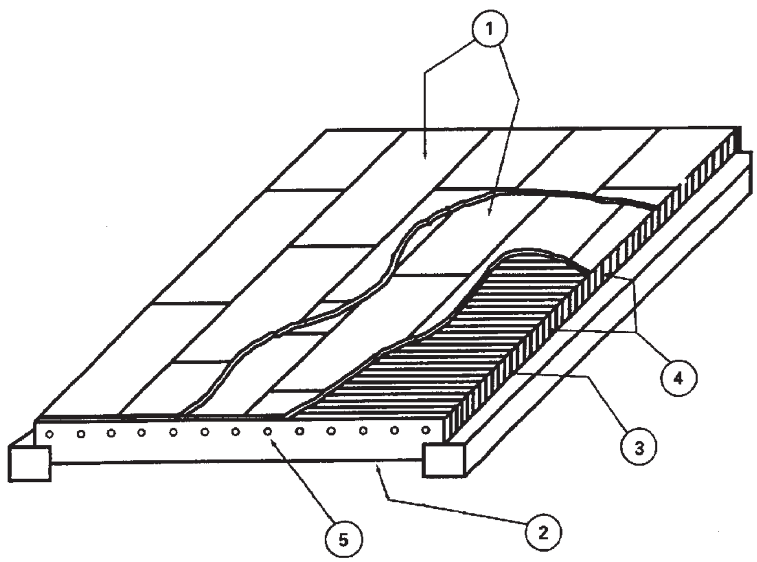


Figure 1-21 Typical 20-foot Deck Section used in the Port Hueneme Demonstration Project Consisting of: 1 - 3/4" Plate; 2 - 1" Plate; 3 - 3/4" Plate; 4 - 5.2" by 14.25" Tubing; 5 - 1" Diameter Rod

The Advanced Waterfront Technologies Test Bed (AWTTB) includes six spans for failure testing of half scale FRP enhanced deck concepts, two spans for full-scale long-term service load testing, and four spans for evaluation of conventional steel protection methods. Some of the AWTTB piles will be prestressed via graphite cables and some of the pile caps will include various FRP elements. Several concepts for rehabilitation/repair of reinforced concrete structures, as well as all-FRP and FRP reinforced/prestressed concrete deck sections will be assessed. Finally, nonstructural composite elements and appurtenances used in waterfront facilities will be evaluated for environmental exposure. [1-21]

The Navy's AWTTB will support the following research activities, with project funding provided by the U.S. Army's CERL and the Navy's Office of Naval Research through FY98:

- ½-scale pier (noted in Figure 1-21);
- Full-scale pier;
- Static and dynamic load (berthing forces) tests;
- Real world durability/constructability evaluation;
- Pre/post-tensioned carbon concrete;
- Pier structural upgrade systems; and
- Pilings and bridge decks.

Fishing Industry

Although the production of commercial vessels has tapered off drastically, there was much interest in FRP trawlers during the early 1970s. These vessels that are still in service provide testimony to the reduced long-term maintenance claims which led to their construction. For example, the 55 foot ***Polly Ester*** has been in service in the North Sea since 1967. Shrimp trawlers were the first FRP fishing vessels built in this country with the ***R.C. Brent***, launched in 1968. Today, commercial fishing fleets are approximately 50% FRP construction. Other aspects of FRP construction that appeal to this industry include increased hull life, reduction in hull weight and cleaner fish holds.

AMT Marine

AMT Marine in Quebec, Canada is probably today's largest producer of FRP commercial fishing vessels in North America. They offer stock pot fishers, autoliners, seiners and stern trawlers from 25 feet to 75 feet. Over 100 craft have been built by the company in the 12 years of their existence, including 80% of all coastal and offshore fishing vessels registered in Quebec in recent years. AMT utilizes Airex® core and a variety of materials and manufacturing processes under the direction of their R&D department to produce rugged utility and fishing craft.

Delta Marine

Delta Marine in Seattle has been designing and building fiberglass fishing, charter and patrol boats for over 20 years. A 70 foot motor yacht has been developed from the highly successful Bearing Sea Crabber. Yachts have been developed with 105 foot and 120 foot molds, which could easily produce fishing boats if there was a demand for such a vessel. The hulls can be fitted with bulbous bows, which are claimed to increase fuel economy and reduce pitching. The bulb section is added to the solid FRP hull after it is pulled from the mold. Delta Marine fabricates sandwich construction decks utilizing balsa core.

LeClercq

Another FRP commercial fishboat builder in Seattle is LeClercq. They specialize in building seiners for Alaskan waters. The average size of the boats they build is 50 feet. At the peak of the industry, the yard was producing 15 boats a year for customers who sought lower maintenance and better cosmetics for their vessels. Some customers stressed the need for fast vessels and as a result, semi-displacement hull types emerged that operated in excess of 20 knots. To achieve this type of performance, Airex® foam cored hulls with directional glass reinforcements were engineered to produce hull laminate weights of approximately three pounds per square foot.

Young Brothers

Young Brothers is typical of a number of FRP boatbuilders in Maine. Their lobster and deck draggers range in size from 30 to 45 feet and follow what would be considered traditional hull lines with generous deadrise and full skegs to protect the props. Solid FRP construction is offered more as a maintenance advantage than for its potential weight savings. Following the path of many commercial builders, this yard offers the same hulls as yachts to offset the decline in the demand for commercial fishing vessels.

Commercial Fishing Fleet

The majority of the FRP fishing fleet in this country was constructed during the 1970s and 1980s. For that reason, a state-of-the-art assessment of the market for those two decades is presented.

The most important application of GRP in the construction of commercial vessels is found in the field of fishery. GRP constructions here offered many potential advantages, particularly in reducing long-term maintenance costs and increased hull life. In addition, GRP offers reductions in hull weight and provides cleaner, more sanitary fish holds. South-Africa GRP-fishing-trawlers of about 25 meters length have been built. Meanwhile, in the USA a few industrial companies have been founded which undertook the building of cutters from GRP. Most of these companies have a quite modern setup with excellent facilities warranting a processing technique as efficient as possible. In design as well as in construction, full attention has been given to economical considerations. When profitable, materials other than GRP may be used.

The materials selected for the GRP structures of these trawlers and cutters are essentially extensions of current pleasure boat practice. Resins are generally non-fire retardant, non air-inhibited rigid polyesters, reinforcing a lay-up of alternating plies of mat and woven roving. The chopper gun is being used in limited areas for depositing chopped strand mat. Several of the designs incorporate sandwich construction in the shell. End grain balsa is the principal core material used, though it has often been restricted to areas above the turn of the bilge to minimize the possibility of core soakage or rotting in the wet bilge areas. Bottom stiffening is generally wood (pine or plywood) encapsulated in GRP. There is some question as to the validity of this practice, due to possible rotting of the wood if the GRP encapsulation is porous, but this method of construction has been used successfully in commercial boats for years and offers sufficient advantages so that it is likely to continue. It is desirable to cover plywood floors and bottom girders with at least 0.25 inches (6mm) of GRP on both sides, so that sufficient reserve strength (bending and buckling) remain if the wood rots.

Plywood is highly favored for the construction of bulkheads and flats. A facing of GRP is applied for water resistance, but the plywood provides strength and stiffness. Wood has also been used extensively for decks in conjunction with GRP sheathing. This extensive use of wood increases the trawler's weight above the optimum values, but represents a significant cost saving. The space between the fish hold and the shell is usually foamed in place, which gives an excellent heat-insulation.

Many GRP trawlers incorporate concrete in the skeg aft for ballast. This has been required in some cases to provide adequate submergence of the propeller and rudder in light load conditions. Thus, the potential weight savings afforded by GRP is often partially reduced by the requirement for ballast. A reinforced concrete beam may be encapsulated in the keel. The use of concrete can be minimized by proper selection of hull shape. GRP construction is generally credited with reducing the hull structural weight, sometimes as much as 50%. However, this saving has not been realized in these trawlers, since hull scantlings have tended to be heavier than theoretically required to increase hull ruggedness and resistance to damage. In addition, the extensive use of wood in the hull structure and non-integral steel fuel tanks has increased hull weight considerably.

Figure 1-22 Typical Trawler Built in the Pacific Northwest in the Late 1970s [Johannsen, 1985]

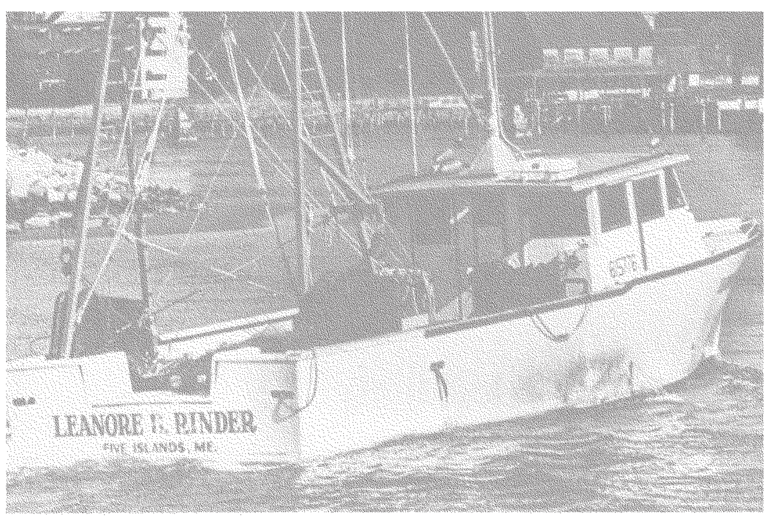


Figure 1-23 Typical Northeast Fishing Vessel Built in the 1970s in High Number and in Limited Production Today [Johannsen, 1985]

In general, it may be stated that when initial expense is of primary importance, wood might be preferred. However, when maintenance costs receive prime consideration, GRP should be chosen. The number of GRP trawlers in the U.S. is still limited, but in spite of the fisherman's conservative nature and the relatively small market, the number of GRP trawlers is slowly increasing, while the production of small GRP fishing boats is advancing. There is a growing interest in GRP trawlers, mainly in the areas of shrimp lobster and salmon fisheries. [1-23]

Fishing boat manufacturers, engaged in building trawlers that range in length from 45 to 85 feet and displace between 35 to 120 tons, initially resisted the obvious appeals of reinforced plastic (RP). It was inconceivable to many fishermen - the romance and tradition of whose trade is so bound up with wooden vessels - that they should go down to the sea in ships made of “plastic.” But here, as in the small pleasure craft industry, economy and utility are winning out over romance and tradition. Approximately 40% of all trawlers manufactured in the United States today are made of RP. [1-24]

Although most of the yards that built the large fishing trawlers in this country during the 1980s are still around, many have moved on to other types of vessels. The industry is simply overstocked with vessels for the amount of ongoing fishing. The Maine boatbuilders that fabricate smaller, lobster-style boats are still moderately active. There has evolved, however, a demand for both trawler and lobster boats for pleasure use.

Lifeboats

The first FRP lifeboats were built in Holland in 1958 when Airex® foam core made its debut in a 24 foot vessel. The service profile of these vessels make them ideally suited for FRP construction in that they are required to be ready for service after years of sitting idle in a marine environment. Additionally, the craft must be able to withstand the impact of being launched and swinging into the host vessel. The ability to economically produce lightweight hull and canopy structures with highly visible gelcoat finishes is also an attribute of FRP construction.

Watercraft America

Watercraft is a 40-year old British company that began operations in the U.S. in 1974. The company manufactures 21, 24, 26 and 28 foot USCG approved, totally enclosed, survival craft suitable for 23, 33, 44 and 58 people, respectively. Design support is provided by Hampton University in England. The vessels are diesel propelled and include compressed air systems and deck washes to dissipate external heat. Figure 1-24 shows the general configuration of these vessels. The plumbing incorporates PVC piping to reduce weight and maintenance. Hull and canopy construction utilizes a spray lay-up system with MIL-1140 or C19663 gun roving. Resin is MIL-R-21607 or MIL 7575C, Grade 1, Class 1, fire retardant

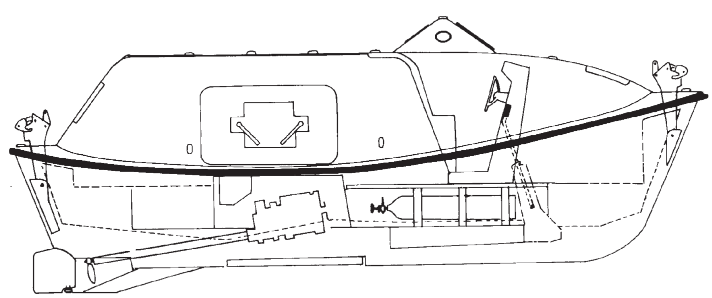


Figure 1-24 Typical Configuration of Watercraft Enclosed Liferaft [Watercraft]

with Polygard iso/npg gelcoat finish. Each pass of the chopper gun is manually consolidated with a roller and overlaps the previous pass by one third of its width. Quality control methods ensure hardness, thicknesses and weight of the finished laminate.

The company has diversified into a line of workboats and “Subchapter T” passenger vessels to offset the decline in the offshore oil business. Reliance Workboats of England and Watercraft America Inc. have teamed up to build the Workmaster 1100 multipurpose boat. The 36 foot boats can travel in excess of 50 mph and can be custom fitted for groups such as customs and law enforcement agencies, commercial or charter fishing operators, and scuba-diving operators. The boat was introduced in Britain in early 1989 and recently in America. [1-8]

Schat-Marine Safety

Another line of lifeboats meeting CFR 160.035 is offered by the Schat-Marine Safety Corporation. Although they claim that fiberglass construction is the mainstay of the lifeboat industry, steel and aluminum hulls are offered in 27 different sizes ranging from 12 to 37 feet with capacities from 4 to 145 persons. Molds for FRP hulls exist for the more popular sizes. These hulls are made of fiberglass and fire retardant resins and feature built-in, foamed in place flotation. The company also manufacturers FRP rigid hull inflatable rescue boats (RIBs), fairwaters, ventilators, lifefloats and buoyancy apparatus.

Naval Applications and Research & Development

According to a study prepared for the U.S. Navy in 1988, the military has been employing composite materials effectively for many years and has an increasing number of projects and investigations under way to further explore the use of composites. [1-1] In 1946, the Navy let two contracts for development of 28 foot personnel boats of laminated plastic. Winner Manufacturing Company used a “bag molding” method while Marco Chemical employed an “injection method.” The Navy used the second method for some time with limited success until about 1950 when production contracts using hand lay-up were awarded. Between 1955 and 1962, 32 Navy craft from 33 to 50 feet in length were manufactured by the “core mold” process, which proved not to be cost effective and was structurally unsatisfactory. [1-25]

During the 1960s, the Navy conducted a series of studies to consider the feasibility of using an FRP hull for minesweepers. In 1969, Peterson Builders, Inc. of Sturgeon Bay, WI completed a 34 foot midship test section. A complete design methodology and process description was developed for this exercise. Although the scale of the effort was formidable, questions regarding economics and material performance in production units went unanswered. [1-26]

Submarines

During the Cold War period, the Navy had an aggressive submarine research and development program that included the investigation of composites for interior and exterior applications. Both these environments were very demanding with unique sets of performance criteria that often pushed the envelope of composites design and manufacturing. The rigors of submarine composites design made partnership with this country's finest aerospace companies a likely match. For surface ship applications, the aerospace approach is generally perceived to not be cost effective.

Submarine Applications

Various submarine structures are made of composite materials, including the periscope fairings on nuclear submarines and the bow domes on combatant submarines. Additionally, the use of filament-wound air flasks for the ballast tanks of the Trident class submarines has been investigated. Unmanned, deep submersibles rely heavily on the use of composites for structural members and for buoyancy. Syntactic foam is used for buoyancy and thick-walled composites are used for pressure housings. One unmanned deep sea submersible, which has a depth rating of 20,000 feet, is constructed with graphite composite by the prepreg fabrication technique. [1-1]

Periscope fairings have been built of FRP since the early 1960s by Lunn Industries. These autoclave-cured parts are precision machined to meet the tight tolerances required of the periscope bearing system. The fairings are all glass, with a recent switch from polyester to epoxy resins. The two-piece fairing is bolted around a metal “I-beam” to form the structural mast. An RTM manufacturer, ARDCO of Chester, PA is currently investigating the feasibility of building the entire structure as a monolithic RTM part, thereby eliminating the metal “I-beam” and bolted sections. Carbon fiber unidirectionals will be added to the laminate to match the longitudinal stiffness of the incumbent structure.

Another Navy program which employs composite materials is the ***Wet Sub***. Its composite components have proven reliable for over 15 years. Both the elevator and the rudders are constructed of a syntactic foam core with fiberglass and polyester skins. The outer skin and hatches, the tail section and the fixed fins on the ***Wet Sub*** are also made of composite materials.

The Navy's ROV and mine hunting/neutralization programs have been using composite materials for structural, skin and buoyancy applications. Current ROVs employ composite skins and frames that are constructed from metal molds using the vacuum bagging process.

The propellers for the MK 46 torpedo are now being made of composite materials. Molded composite propeller assemblies have replaced the original forged aluminum propellers. The composite propellers are compression molded of glass fiber reinforced polyester resin. Advantages of the new composite propellers include weight savings, chemical inertness and better acoustic properties. Elimination of the metal components markedly reduces delectability. Additionally, studies have projected this replacement to have saved the program a substantial amount of money.

A submarine launched missile utilizes a capsule module that is constructed of composite materials. The capsule design consists of a graphite, wet, filament-wound sandwich construction, metal honeycomb core and Kevlar® reinforcements. Several torpedo projects have investigated using a shell constructed of composites, including a filament-wound carbon fiber composite in a sandwich configuration where the nose shell of the torpedo was constructed with syntactic foam core and prepreg skins of carbon and epoxy resin. Testing revealed a reduction in noise levels and weight as compared to the conventional aluminum nose shell. Research at NSWC, Annapolis and conducted by Structural Composites, Inc. indicates that composite materials have great flexibility to be optimized for directional mechanical damping characteristics based on material selection, orientation and lay-up sequence. [1-1]

Submarine Research & Development Projects

Numerous investigations conducted by the Carderock Division of NSWC have done much to advance our understanding of the performance of composites in a marine environment, even if some of the prototype structures have not found their way into the fleet. For internal applications, the recently released military standard for performance of composites during fires outlines rigorous test and evaluation procedures for qualification. For structural elements, the critical nature of submarine components serves as a catalyst for increasing our analytical and design capabilities.

The Advanced Research Projects Agency (ARPA) recently sponsored a multi-year project to build dry deck shelter components using thermoplastic resin systems. The goal of this project is to get these highly-specialized structural materials down from $400/pound to $100/pound. Additional objectives, according to ARPA's Jim Kelly, include development of advanced composite fabrication technologies and embedded sensor technology. [1-16]

As outlined in the 1990 National Academy of Science report "*Use of Composite Materials in Load-Bearing Marine Structures,*" [1-16] the Navy has targeted several specific applications for composites on submarines. Table 1-2 summarizes these projects and the ARPA effort, along with status, participants and design challenges.

Table 1-2 Recent Submarine Research & Development Composites Programs

Application	Participants and Status
Dry Deck Shelter The existing steel Dry Deck Shelter is composed of four major segments, the hyperbaric sphere which serves as a decompression chamber, the access sphere which permits access to the Hanger and to the hyperbaric sphere, the Hanger, which stores the Swimmer Delivery Vehicle, and the Hanger Door. The composite design has a joint in the middle of the hanger to test this critical technology. [1-27]	General Dynamics EB Division is the overall design agent and is building the rear half of the Hanger of carbon/PEEK or PPS. Grumman Aerospace is building the Hanger Door; McDonnell Douglass Aircraft is building the Forward Hanger and Hyperbaric Sphere using PEEK and woven/braided/stitched glass/carbon preforms and a 4-foot diameter section has been built and tested to 120% design pressure; and Lockheed is building the Access Sphere from carbon/PEEK.
Propulsion Shaft A thick-sectioned, filament wound tube was developed that resulted in a cost-effective, fatigue-resistant propulsion shaft. The section of the shaft between the first inboard coupling and the propeller will be tested in demonstrations aboard the ***Memphis***.	Brunswick Defense has filament wound a number of prototype shafts for testing, including a 3-inch thick, 3-foot diameter section. Concurrent programs are at NSWC, Annapolis for the Navy's oiler fleet and training vessels under the guidance of Gene Camponeschi and George Wilhelmi. [1-28]
Control Surfaces This demonstration focuses on hydrodynamically loaded structures, initially fairwater planes, to be tested on the ***Memphis***. Construction employs a simple box spar for stiffness and syntactic foam cells to provide the correct hydrodynamic form.	Newport News Shipbuilding recently completed the design, analysis, fabrication and testing of a control surface for a small submersible [1-33]. General Dynamics EB Division built all-composite diving planes for the NR-1 that included a carbon shaft that transitioned to a titanium post.
Air Flasks This is a straightforward application aimed at weight reduction. Most of the sub-scale testing was completed under ONT technology block programs. The primary remaining issue is service life.	Impetus for this program has waned somewhat as certification procedures for metal flasks have been updated and the location of the weight saved will not now appreciably improve the performance of the submarine.
Engine Room Composites Applications The project goal was to develop generic design technology for machinery foundations and supports. The technology demonstrator is a 1/4-scale main propulsion engine subbase. This will be followed by a yet-to-be-selected full-scale application to demonstrate the technology.	Westinghouse has built some prototype composite foundations, including one designed for a submarine main propulsion plant. Although superior damping characteristics can be achieved with composite structures, improved performance is not a given as structures need to be engineered based on stiffnesses and weights. Fire issues have put this effort on hold.
Fairwater This demonstration involves a large, nonpressure-hull, hydrodynamic structure which, if built, would enhance ship stability through reduction of topside weight. Use of composites might also facilitate novel fairwater designs as might be required to accommodate new functions within the sail and to reduce wake.	Currently under development, the design for a next generation fairwater will largely be dictated by mission requirement (size) and hydrodynamics (shape). Composites may offer the opportunity to improve functionality at reduced weight and cost.
Stern Structure This demonstration, involving a large, nonpressure-hull, hydrodynamic structure would carry the fairwater demonstration a step further. It is expected to lead to the development of a structural “system” which will provide the basis for an all-composites outer hull for future designs.	General Dynamics EB Division built a 1/10 scale model of a submarine stern section of glass/epoxy prepreg. The goal of the prototype was to demonstrate weight savings, maintenance reduction and acoustic and magnetic signature reduction. NSWC conducted “whipping” analysis and shock testing of the model.
Bow Structure The Navy has long made use of composite materials for construction of bow domes that are structural yet allow for sonar transmission. These glass-epoxy structures are believed to be the world's largest autoclave-cured parts. More recently developed is a complete bow section of the NR-1 research submarine.	The bow dome development program was undertaken by HITCO. In 1986, HITCO completed a rigorous test program to qualify impact resistant epoxy prepreg systems. [1-29]. An extensive composite bow section of the NR-1 was built by Lunn.

Surface Ships

Application of composite materials within the U.S. Navy's surface ship fleet has been limited to date, with the notable exception of the coastal minehunter (MHC-51). Recently, however, there has been growing interest in applying composite materials to save weight; reduce acquisition, maintenance and life-cycle costs; and enhance signature control. The Navy is considering primary and secondary load-bearing structures, such as hulls, deckhouses and foundations; machinery components, such as piping, valves, pumps and heat exchangers; and auxiliary items, such as gratings, ladders, stanchions, ventilation ducting and waste handling systems. These applications have generated research and prototype development by the Navy to verify producability, cost benefits, damage tolerance, moisture resistance, failure behavior, design criteria, and performance during fires. [1-30] In certain areas, the needs of the Special Warfare community have served to accelerate the use of composite construction.

Patrol Boats

The Navy has numerous inshore special warfare craft that are mainly operated by the Naval Reserve Force. More than 500 riverine patrol boats were built between 1965 and 1973. These 32 foot FRP hulls had ceramic armor and waterjet propulsion to allow shallow water operation.

Production of GRP patrol craft for the Navy has not always proven to be profitable. Uniflite built 36 special warfare craft, reportedly of GRP/Kevlar® construction, to support SEAL operations in the early 1980s and has since gone out of business. The Sea Viking was conceived as a 35 foot multi-mission patrol boat with provisions for missiles. The project suffered major design and fiscal problems, including an unacceptable weight increase in the lead ship, and eventually its builder, RMI shipyard of San Diego, also went out of business.

Figure 1-26 SMUGGLER 384 Built by Smuggler Marine of Sweden [*Jane's High-Speed Craft*]

Sweden's Smuggler Marine has been producing boats similar to the one shown in Figure 1-26 since 1971. The Swedish Navy, Indian Coast Guard and others operate these vessels.

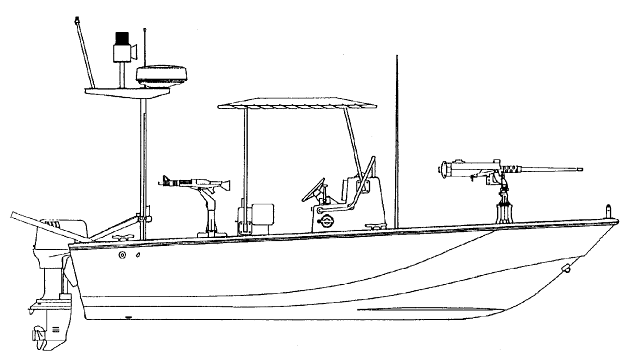


Figure 1-27 22-Foot Utility Boat (MK II) Produced by Willard Marine, Inc. [courtesy of Willard Marine, Inc.]

Willard Marine has successfully been building boats for the U.S. Coast Guard and U.S. Navy for over 30 years. Some 700 boats to 70 different government specifications have been completed since 1980. Willard uses conventional construction methods: mostly hand lay-up of solid or sandwich laminates (according to contract specs) with some impregnator use. Their efficient use of a 50,000 square-foot facility and close management of production (100 boats per year) contributes to the longevity of this firm. They have also built private power and sail yachts, a 125-foot research vessel and now market a commercial version of their 18, 22 and 24 foot Rigid Inflatable Boat (RIB). Figure 1-27 shows a typical military boat produced by Willard.

U.S. Navy warships were threatened in 1988 during the Iranian Persian Gulf conflict by small, fast Iranian Revolutionary Guard gunboats. After capturing one, the Navy began using it for exercises off San Diego and became impressed with the capabilities of this size vessel. Recognizing the cost effectiveness of this type of vessel and the range of mission capabilities, procurement of tthis type of craft for operation with Special Boat Units started. Figure 1-28 shows a typical fast patrol boat design, this one from McDonnell Douglas and Magnum Marine. The U.S. is slightly behind its European counterparts in the exploitation of these types of vessels in support of naval operations. Many countries have opted not to develop navies based on ships with offshore capabilities and instead rely on fast, heavily armed patrol craft. Fast patrol boats around 100 feet in length, like the one shown in Figure 1-29, offer increased capability and endurance over the smaller "cigarette" type vessels.

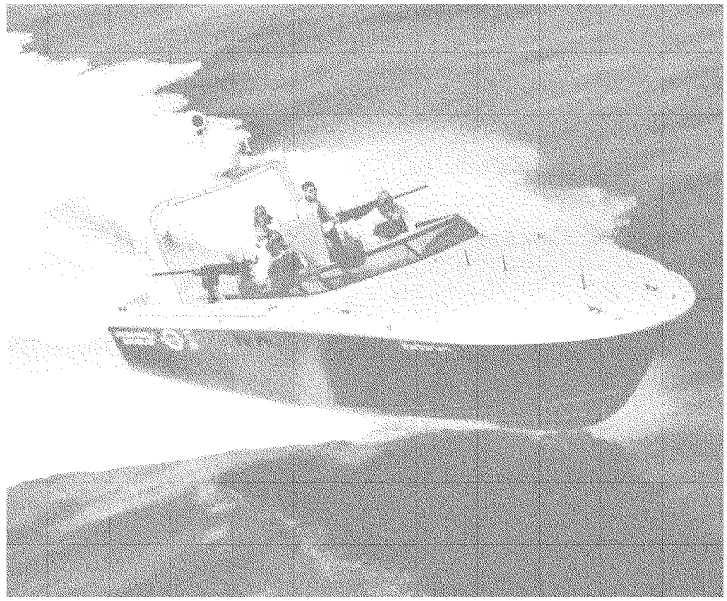


Figure 1-28 Fast Patrol Boat BARBARIAN [McDonnell Douglas and Magnum Marine]

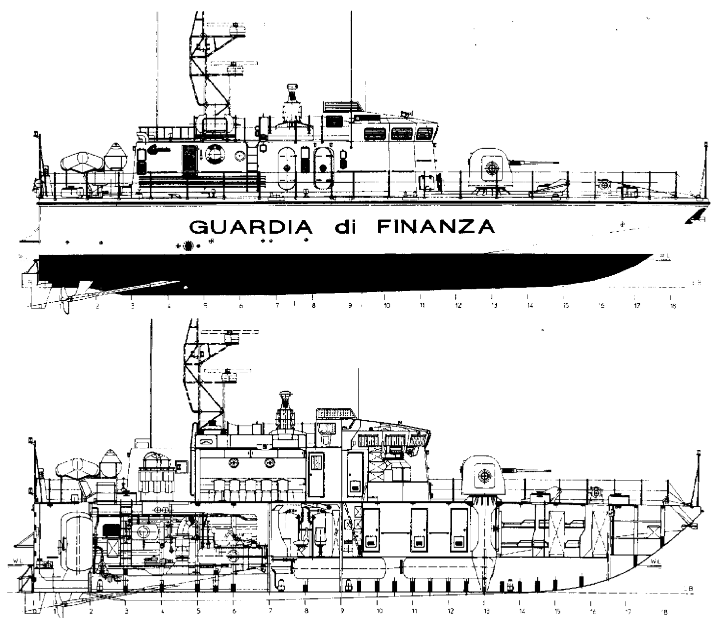


Figure 1-29 MV85 BIGLIANI Class 45-Knot Fast Patrol Craft from Crestitalia SpA, Italy [Jane's High-Speed Craft]

The U.S. recently conducted a design competition for the Mark V Special Operations Craft to support SEAL operations. Halter Marine offered a composite boat with surface piercing propellers and an aluminum boat with waterjet propulsion. Peterson Builders built an aluminum catamaran. The aluminum waterjet boat was chosen after testing in the Gulf of Mexico by the Special Warfare group at McDill Air Force Base in Tampa, FL. The operational assessment probably did not consider hull construction material as much as performance, although some concern was noted regarding future repair of the composite hull. This is interesting to note, as most of the boats used by Special Operations forces are of GRP construction. Table 1-3 is an international overview of composite military high-speed craft.

Table 1-3 Composite Military High-Speed Craft Overview

Country	Yard	Length	Speed	Construction
Denmark	Danyard Aalborg A/S	54 m	30 knots	GRP sandwich
Italy	Cantieri Navali Italcraft	22 m	52 knots	GRP
	Crestitalia SpA	27 m	45 knots	GRP
	Intermarine SpA	23 m	40 knots	GRP
		27 m	40 knots	GRP
Spain	Polyships S.A.	17 m	67 knots	Kevlar®, carbon, glass, polyester
Sweden	Smuggler Marine AB	25m	55 knots	sandwich GRP
	Swedeship Composite AB	13.5 m	72 knots	Kevlar®, R-Glass, carbon fiber prepreg
Thailand	Technautic Intertrading Co.	26 m	27 knots	GRP sandwich with Airex core
United Kingdom	Ailsa-Perth Shipbuilders	25 m	39 knots	GRP
	Colvic Craft Plc.	16 m	35 knots	GRP
	Paragon Mann Shipyard	50 ft	55 knots	Kevlar®, R-Glass, carbon fiber monocoque
	Vosper Thornycroft (UK)	30 m	28 knots	GRP hull and aluminum superstructure
United States	Boston Whaler	25 ft	40 knot	foam filled GRP
	Fountain Power Boats	42 ft	60 knots	GRP
	McDonnell Douglas/Magnum Marine	40 ft	48 knots	Kevlar®/GRP
	Tempest Marine	43.5 ft	50 knots	GRP
	Uniflite	36 ft	32 knots	Kevlar®/GRP

Mine Counter Measure Vessels

The U.S. Navy in FY 1984 had contracted with Bell Aerospace Textron (now Textron Marine) to design and construct the first of 14 minesweeper hunters (MSH). The hulls were GRP monohulls utilizing surface effect ship technology. Tests showed that the design could not withstand explosive charges and subsequent redesign efforts failed.

In 1986, a contract was issued to Intermarine USA to study possible adaptations of the ***Lerici*** class craft to carry U.S. systems. The ***Lerici*** is 167 feet (50 meters) and is made with heavy single skin construction that varies from one to nine inches and uses no frames. Intermarine, USA of Savannah, GA and Avondale Shipyards of New Orleans, LA were selected to build this class for the U.S. Navy. Current plans call for a total of twelve Osprey class minehunters to be built (8 at Intermarine, 4 at Avondale). [1-31]

Both structural and manufacturing aspects of the Italian design were studied extensively by the U.S. Navy. Numerous changes to the ***Lerici*** design took place to allow for U.S. Navy combat systems; damage and intact stability; and shock and noise requirements. [1-32] Table 1-4 lists some of the characteristics of the ***Osprey*** class minehunter. [1-33]

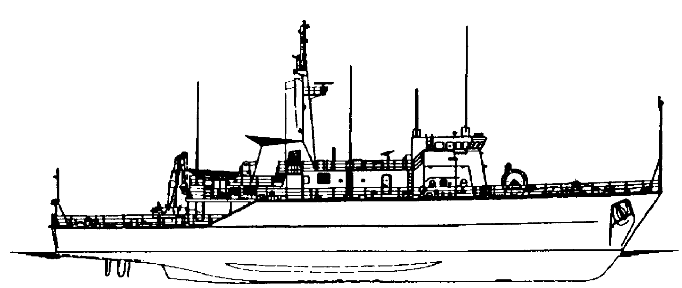
Table 1-4 Characteristics of the U.S. Navy *Osprey* Class Minehunter

Length:	57.2 meters (187 feet, 10 inches)
Beam:	11.0 meters (35 feet, 11 inches)
Draft:	2.9 meters (9 feet, 4 inches)
Displacement:	895 metric tons
Propulsion:	two 800 hp amagnetic diesel engines with variable fluid drives turning two cycloidal propellers
Accommodations:	5 officers; 4 CPO; 42 enlisted

Construction Particulars

All glass reinforcement for primary structure is E glass. Spun woven roving of 1400 grams per square meter is used for the hull, transverse bulkheads, and decks. The spun woven roving is a fabric with the weft direction reinforcement consisting of rovings that have been "tufted." This treatment, which gives the fabric a fuzzy appearance, improves the interlaminar shear strength over traditional woven rovings. The superstructure is constructed of a "Rovimat" material consisting of a chopped strand mat stitched to a woven roving. Stitching of the two fabrics was chosen to improve performance with the semi-automated resin impregnator (which is used during the lamination process). The total weight of the Rovimat is 1200 grams per square meter (400 g/m^2 mat + 800 g/m^2 woven roving).

The resin is a high grade toughened isophthalic marine polyester resin. It is specially formulated for toughness under shock loads and to meet the necessary fabrication requirements. The resin does not have brittle fracture characteristics of normal polyester resins, which gives it excellent performance under underwater explosive loads. Combined with spun woven roving, the laminate provides superior shock and impact resistance. The resin formulation has been optimized for improved producibility. Significant is the long gel time (up to four hours) with low exotherm and a long extended delay time to produce a primary bond. [1-32]



The Swedish and Italian Navies have been building minesweeping operations (MSO) ships with composite technology for many years. The Swedish Navy, in conjunction with the Royal Australian Navy and the U.S. Navy, studied shock loadings during the development of the Swedish composite MSO. Shock loadings (mine explosion simulations) were performed on panels to study candidate FRP materials and configurations such as:

- Shapes and different height/width ratio of frames;
- Epoxy frames;
- Sprayed-up laminates;
- Corrugated laminates;
- Sandwich with different core densities and thicknesses;
- Different types of repairs;
- Weight brackets and penetrations on panels;
- Adhesion of fire protection coatings in shock;
- The effect of double curved surfaces; and
- Reduced scale panel with bolted and unbolted frames.

This extensive testing program demonstrated that a frameless Glass Reinforced Plastic (GRP) sandwich design utilizing a rigid PVC foam core material was superior in shock loading and resulted in better craft and crew survivability. The Swedish shock testing program demonstrates that when properly designed, composite materials can withstand and dampen large shock loads. [1-34] Table 1-5 summarizes the current use of FRP for mine counter measure vessels. Although design and performance issues associated with sandwich construction for minehuntershave been demonstrated, most recent new orders for minehunters worldwide are for thick-sectioned, single-skin construction.

Swiftships of Morgan City, LA is primarily a yard that builds in aluminum and steel. A contract with the Egyptian Navy created the opportunity for this yard to get involved with composite construction. Three of these 100-foot vessels, shown at right, have been delivered. Swiftship's Program Engineer largely credits the resources and research work of the U.S. Navy with making the transition to composite construction possible for this medium-sized yard.

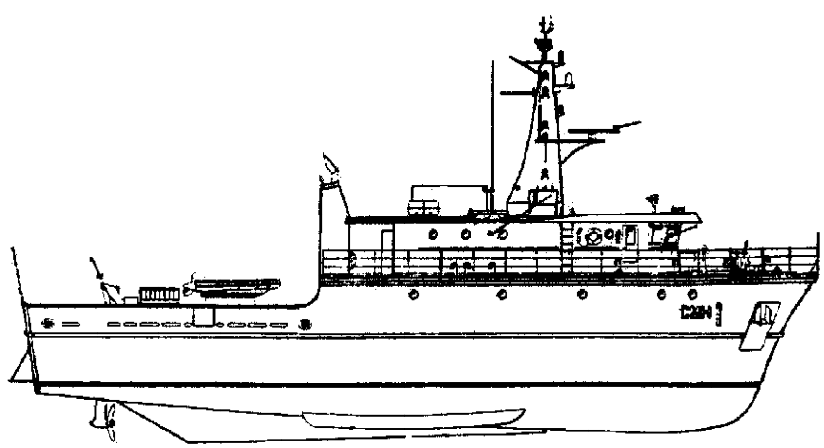


Figure 1-30 Profile and Equipment Layout of the Swift-ships 33.5m CMH [June, 94, WARSHIP TECH]

Table 1-5 shows the evolution of some key classes of mine counter measure vessels that have been developed in Europe since 1960. In the 1960s, the United Kingdom built the ***HMS Wilton***, the first GRP minesweeper. These ships were commissioned in 1973, closely followed by the ***Hunt*** Class. Both these vessels used isophthalic resin with up to 47 layers of woven roving in the hull. The ***Tripartite*** Class minehunter was jointly developed by France, Belguim and the Netherlands [1-35]. Intermarine's venerable ***Lerici*** class has undergone numerous modifications to suit the needs of various countries, including the United States and most recently Austrailia.

Table 1-5 Current FRP Mine Counter Measure Vessels [1-23, 1-31]

Type of Construction	Class	Country	Builder	Built (1995)	Total	Δ (tons)	LOA (m)	Speed (kts)
Stiffened Single Skin	***Wilton***	United Kingdom	Vosper Thornycroft	1	1	425	46	15
	Hunt	United Kingdom		13	13	625	60	17
	Sandown	United Kingdom		5	9	378	52.5	14
	Sandown	Saudi Arabia		3	3	378	52.5	14
	Mod. ***Sandown***	Spain	Bazan	0	8	530	54	15
	Aster	Belgium	Beliard	7	7	544	51.5	15
	Eridan	France	Lorient Dockyard	9	10	544	49.1	15
	Munsif	Pakistan		2	3	535	51.6	15
	Alkmaar	Netherlands	Van der Giessen-de Norde	15	15	588	51.5	15
	Mod. ***Alkmaar***	Indonesia		2	2	588	51.5	15
	Kiskii	Finland	Oy Fiskars AB	7	7	20	15.2	11
Foam Sandwich	***Landsort***	Sweden	Karlskronavarvet	8	8	360	47.5	15
	Landsort	Singapore	Karlskronavarvet	2	4	360	47.5	15
	YSB	Sweden	Karlskronavarvet	0	4	175	36	12+
	Bay	Austrailia	Carrington	2	2	170	30.9	10
	Stan Flex 300	Denmark	Danyard Aalborg A/S	8	14	300	54.0	30+
Unstiffened, Thick Skin	***Lerici***	Italy	Intermarine, SpA	4	4	520	50	15
	Gaeta	Italy		6	6	720	52.5	15
	Lerici	Nigeria		2	2	540	51	15.5
	Kimabalu	Malaysia		4	4	540	51	16
	Modified ***Lerici***	South Korea	Kang Nam	6	12	540	51	15.5
	Gaeta	Austrailia	Newcastle	0	6	720	52.5	15
	Osprey	United States	Intermarine, USA/ Avondale	3	12	660	57.3	12

Components

Composite ship stacks are also under investigation for the U.S. surface fleet. Non-structural ship components are being considered as candidates for replacement with composite parts. Two types of advanced non-structural bulkheads are in service in U.S. Navy ships. One of these consists of aluminum honeycomb with aluminum face sheets, and the other consists of E-glass FRP skins over an aramid core material. [1-1]

The Naval Surface Warfare Center, Carderock contracted for the construction of a shipboard composite foundation. An open design competition attracted proposals featuring hand lay-up, resin transfer molding, pultrusion and filament winding. A filament wound prototype proposed by Brunswick Defense was selected, in part, because the long term production aspects of the manufacturing process seemed favorable. The foundation has successfully passed a shock test.

Development of composite propulsion shafts for naval vessels is being investigated to replace the massive steel shafts that comprise up to 2% of the ship's total weight. Composite shafts of glass and carbon reinforcing fibers in an epoxy matrix are projected to weigh 75% less than the traditional steel shafts and offer the advantages of corrosion resistance, low bearing loads, reduced magnetic signature, higher fatigue resistance, greater flexibility, excellent vibration damping and improved life-cycle cost. [1-1]

The U.S. Navy studied the benefits of hydrofoils in 1966. The USN experimental patrol craft hydrofoil **(PCH-1)** ***Highpoint*** was evaluated for weight savings. The overall weight savings over HY 80 steel were 44% for glass reinforced plastic, 36% for titanium alloy and 24% for HY 130 steel. In the mid 1970s a hydrofoil control flap (Figure 1-31) and a hydrofoil box beam element applying advanced graphite-epoxy composites were evaluated by the Navy. [1-9]

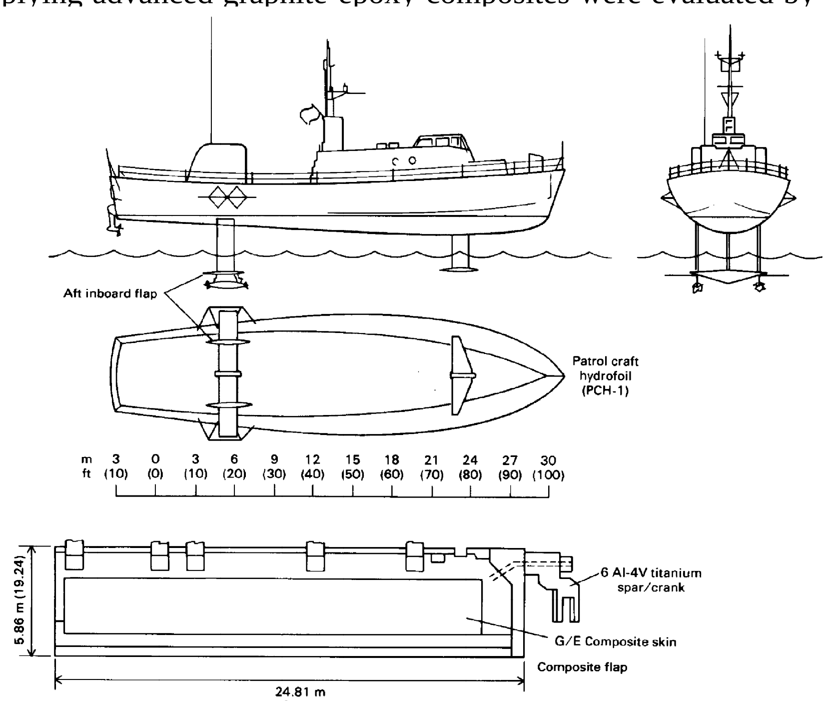


Figure 1-31 U.S. Navy Patrol Craft Hydrofoil (PCH-1) Composite Flap [*ASM Engineer's Guide to Composite Materials*]

Table 1-6 Recent Navy Composite Machinery Application Projects [George Wilhelmi, Code 823, NSWC, Annapolis]

Program	Objective	Status
Standard Family of Centrifugal Pumps	"Affordability" through Navy-owned standardized design; max. interchangeable pump components; and improved performance & reliability with composite wetted parts	Prototype manufacturing has started under design contract awarded to IDP in March 1992
Glass-Reinforced Plastic (GRP) Piping Systems	Develop tech. base & design guidance for max. utilization of MIL-P-24608A GRP piping material in non-vital systems to 200 psig at 150°F; to reduce life-cycle costs associated with corrosion/erosion of Cu-Ni and steel in seawater	Design practices manual/ uniform-industrial process instruction & shock guidance completed; optimization of fire protective insulation underway
Composite Ball Valves	Develop low-maintenance, affordable composite ball and flow control valves suitable for 200 psig/150°F service in metallic and nonmetallic piping systems	Lab evaluation of commercial valve complete; ship evaluation underway; marinization strategies developed
Composite Ventilation Ducting	Develop corrosion-free, fire-resistant, light weight ducting to replace galvanized steel and aluminum in air supply and exhaust applications suffering accelerated corrosion damage	1st surface ship application aboard CVN71 in Feb 93 and trial installation on CG-47 class in FY95. GLCC now optimizing process and fire hardening
Composite Resilient Machinery Mounts	Develop lightweight, corrosion-free, shock-rated composite version of standard EES-type resilient machinery	Composite prototype mounts passed hi-impact shock requirements, impact shock requirements; (6.2) near completion; requires extension over light and medium load weight range
Composite Diesel Engine	Develop lightweight, low-magnetic signature marine diesel engine employing metal, polymer, and ceramic matrix composite materials	ONR, GLCC and private American diesel manufacturers have teamed to accelerate 6.2 R & D
Composite Propulsion Shafting	Develop lightweight, corrosion-free, propulsion shafting with tailorable properties for acoustic and magnetic silencing benefits	Full-diam, short length, 50,000 HP AOE composite section evaluated in lab test fixture with encouraging results
Composite Nuts & Bolts; Ladders; Grates; Screens Pump Impellers; etc.	Exploit composites developed for U.S. chemical processing industry to solve chronic corrosion problems with steel and Cu-Ni in sewage tank and flight deck applications	Most shipboard installations are proving successful following 2 to 5 years of onboard experience

Conventional heat exchangers use copper alloy tubes to transport seawater as a cooling medium. The copper-nickel tubes have high heat transfer rates, but they are subject to corrosion, erosion and fouling. The deteriorating tubes force operators to run the equipment at reduced flow rates, which in turn reduces the overall effectiveness. Composite materials offer the potential to eliminate corrosion and erosion problems, as well as reduce the weight of heat exchanger assemblies. An ongoing study by Joseph Korczynski, Code 823, NSWC, Annapolis is looking at candidate composite materials that were optimized to increase thermal conductivity, a characteristic not usually associated with these types of materials. Figure 1-32 illustrates the encouraging results of this program.

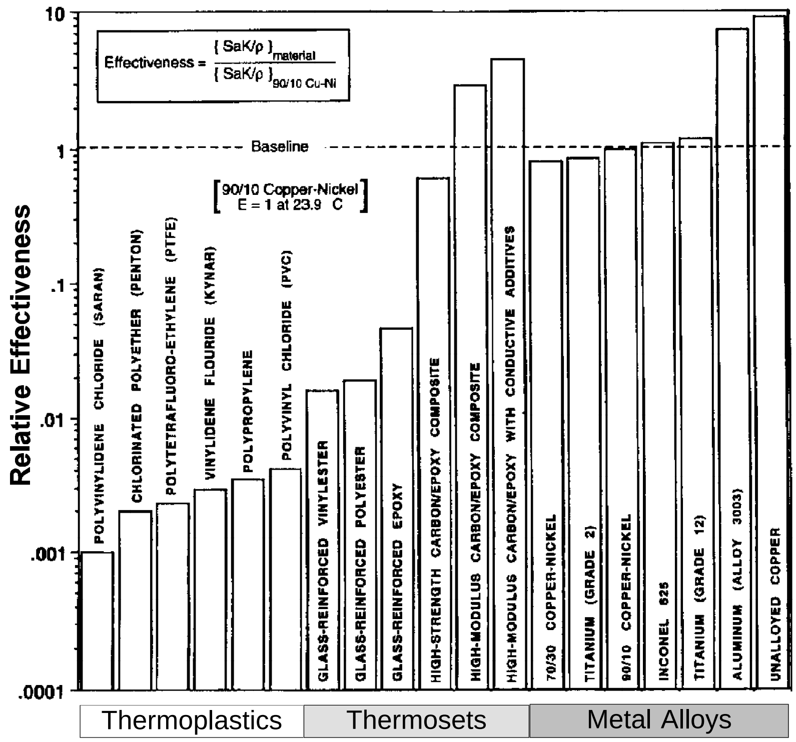


Figure 1-32 Ranking of Effectiveness (Allowable Stress, Conductivity over Density) of Various Materials Considered for Heat Exchangers [Joseph Korczynski, Code 823, NSWC, Annapolis]

Composite piping system fire survivability has also been evaluated using glass reinforced epoxy and vinyl ester piping systems with various joining methods and under dry, stagnant water, and flowing water conditions. The results of these tests have been compared with metallic alternatives. For example, 90-10 Cu-Ni Sil-brazed joints survive 2-3 minutes with dry pipe and less than 20 minutes with stagnant water in the pipe. Epoxy pipe assemblies survived less than 3 minutes in a full-scale fire when pressurized to 200 psig stagnant water. The joints failed catastrophically. However, application of a promising fire barrier around the pipe joints improved survivability time to 23 minutes, and a completely insulated assembly survived for 30 minutes with no leaks after the fire.

One of the most successful Navy composites machinery program to date involves the development of a standard family of composite centrifugal pumps. The pumps employ a limited number of housing sizes, impellers, and drives to cover a wide range of pressure and flow rate requirements. The pump housing can be fabricated from glass-reinforced epoxy, vinyl ester, or polyester. High velocity erosion investigations with various fiber reinforced polymer matrix composite pump materials showed excellent corrosion-erosion performance of composites relative to gun metal bronze (widely used in marine centrifugal pumps) over a velocity range of 0 to 130 ft/sec. However, the composites did not fare as well under cavitation conditions, where they showed generally inferior performance to the bronze. In most marine pump applications, however, cavitation is not expected to be a problem. [1-30]

Advanced Material Transporter (AMT)

A recent Navy project that encompasses the total design and fabrication of a composite hull structure is the Advanced Material Transporter (AMT), where a 0.35 scale model was built.

The material selected for the AMT was an E-glass woven roving fabric and vinyl ester resin. Seemann Composites lnc. was contracted to fabricate the entire ship hull and secondary structures of the AMT model using the Vacuum Assisted Resin Transfer Molding (VARTM) process. A modular construction approach was used to fabricate large components of the AMT, which were later assembled using a combination of bolting and bonding. The fabric reinforcement for the primary hull was laid up dry for the full thickness of the hull, and the resin was injected in one stage in only three and a half hours. The hull was cured at room temperature overnight and then longitudinal hat-stiffeners were fabricated in-place onto the boat hull.

The 40-ft long cargo deck was fabricated using a 0.5-in. thick balsa core sandwich construction, and then room temperature cured overnight. Deep longitudinal hat-stiffener girders were fabricated in-place onto the deck bottom, similar to the girders on the ship hull. The bulkheads and superstructure were built using the same general approach as the main deck. Some of the critical joints for the main deck and bulkheads to the hull were completed using VARTM and other less critical connections were fabricated using hand lay-up. To reduce the time required for post curing, the entire boat hull was fully assembled and then post cured at an elevated temperature of 120°F for eight hours. The estimated structural weight for the model is 7000-lbs, which is 30% lighter than an aluminum hull concept. [1-36]

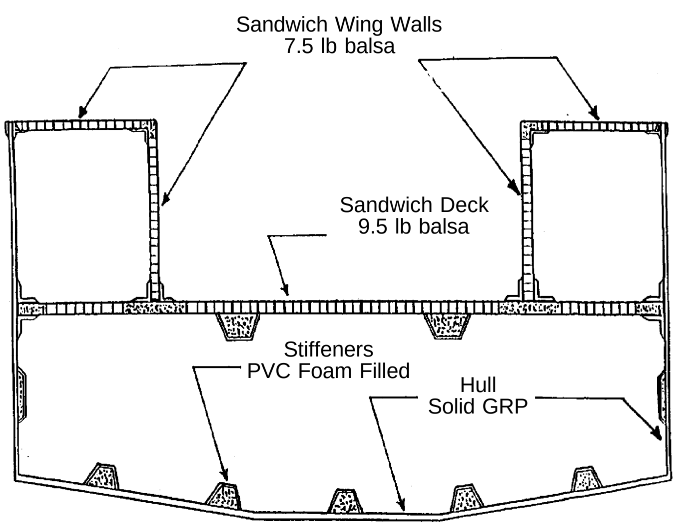


Figure 1-33 Lay-up Configuration for AMT Validation Model [Nguyen, *93 Sml Boat*]

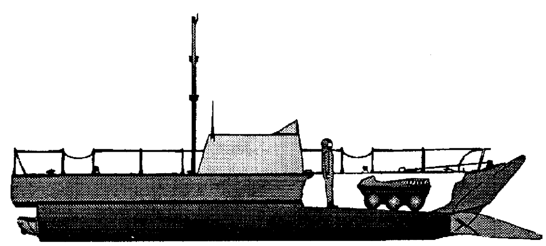


Figure 1-34 Profile of AMT Validation Model [Nguyen, *93 Sml Boat*]

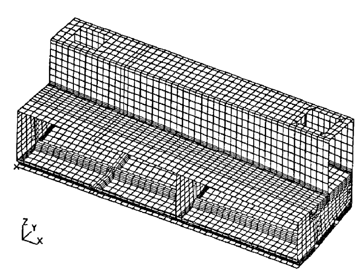


Figure 1-35 Midships FEM of AMT Validation Model [Nguyen, *93 Sml Boat*]

Deckhouse Structure

The U.S. Navy has made considerable progress recently in the development and demonstration of blast-resistant composite design concepts and prototypes for deckhouses, superstructures and other topside enclosures for naval combatants. These composite concepts offer significant advantages over conventional steel structures, including a 35 to 45% reduction in weight, reduced corrosion and fatigue cracking, and improved fire containment. [1-37]

A single-skin stiffened and a sandwich core concept have been developed for topside applications. The stiffened concept involves the assembly of prefabricated hat-stiffened GRP panels using prefabricated GRP connection angles and bolted/bonded joint details. Panel stiffeners are tapered to maximize peel resistance, to minimize weight, and to simplify the joints and panel connections. The sandwich concept utilizes prefabricated sandwich panels that are attached through bolting and bonding to a supporting steel framework. A steel framework is attractive for the construction of composite topside structures since it is readily erected in a shipyard environment, allows for the attachment of prefabricated high-quality GRP panels, and provides resistance to collapse at elevated temperatures under potential fire insult.

France's newest frigate makes use of glass/balsa core panels made with polyester resin for both deckhouse and deck structure to reduce weight and improve fire performance as compared to aluminum. The shaded areas of figure 1-38 shows the extent of composite sandwich construction. [1-38]

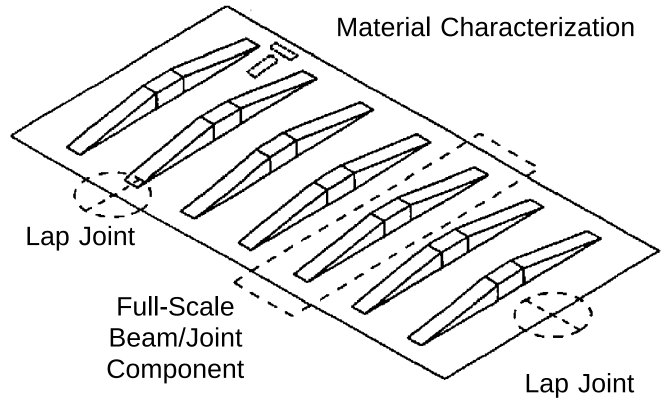


Figure 1-36 Hat-Stiffened Deckhouse Panel Test Elements [Scott Bartlett, NSWC]

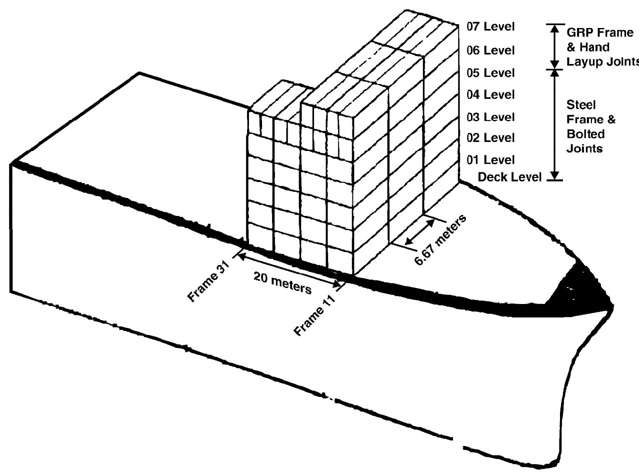


Figure 1-37 Arrangement of GRP Deckhouse Proposed for the SSTDP Sealift Ship [Scott Bartlett, NSWC]

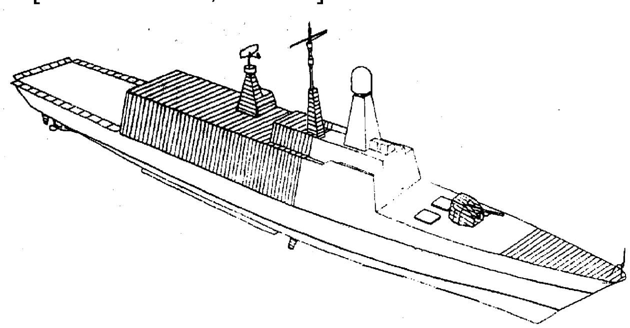


Figure 1-39 French LA FAYETTE Class Frigate Showing Area Built with Balsa-Cored Composites [DCN Lorient, France]

Advanced Hybrid Composite Mast

The Advanced Enclosed Mast/Sensor (AEM/S) project represents a chance for the U.S. Navy to evaluate the first large-scale composite component installed onboard a surface combatant. The sandwich structure is designed to support and protect an array of sensors typically found mounted on metallic masts erected using truss elements. The AEM/S has fully integrated sensor technology, electromagnetics, and signature reduction made possible by the engineering latitude of today's composite materials. Extensive material and structural testing preceded the fabrication of the mast at Ingalls Shipyard in Pascagoula, MS. The Advanced Enclosed Mast/Sensor (AEM/S) is an 87-foot high, hexagonal structure that measure 35 feet across. The 40-long ton structure was fabricated in two halves using the SCRIMP® process. Conventional marine composite materials, such as E-glass, vinyl ester resin and balsa and foam cores are utilized throughout the structure. Because mechanical joints were engineered into both the middle and the base of the structure, a lot of analytical and testing focused on bolted composite joints.

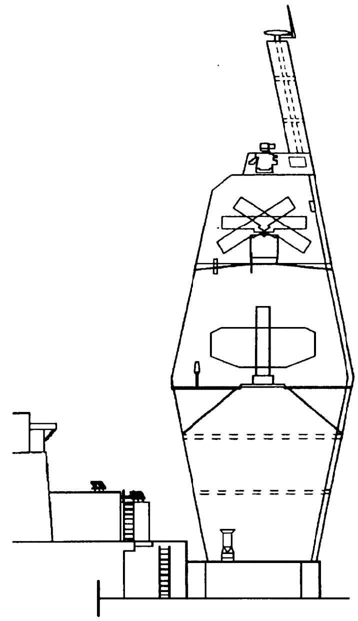


Figure 1-39 Configuration of the Advanced Enclosed Mast/Sensor [NSWC, Carderock]

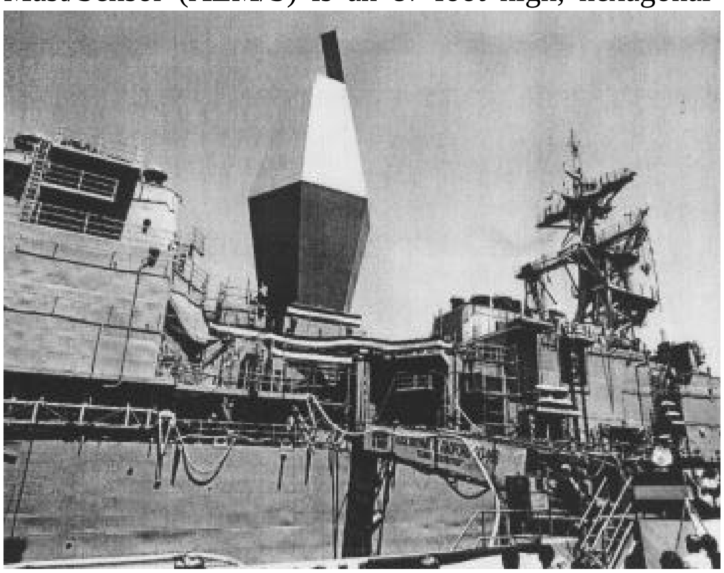


Figure 1-40 Advanced Enclosed Mast/Sensor (AEM/S) at Stepping Ceremony on the ***USS Radford*** DD 968 [NSWC, Carderock]

GLCC Projects

The GLCC has collaborated with the Navy on a number of surface ship applications of composite mateials, including ventilation ducting, electronics enclosures, topside structure and a replacement rudder for the MCM minehunter class. The composite MCM rudder is 50% of the weight for a metallic counterpart at a simialr cost, with anticipated reduced corrosion-related life-cycle costs. A closed-mold resin infusion process (RIRM) was validated for massive ship structural parts.

Figure 1-41 The MCM Composite Rudder RIRM process [Structural Composites]

Transportation Industry

The transportation industry represents the best opportunity for growth in structural composites use. As manufacturing technologies mature, the cost and quality advantages of composite construction will introduce more, smaller manufacturers into a marketplace that will be increasingly responsive to change. [1-39] Current FRP technology has long been utilized in the recreational vehicle industry where limited production runs preclude expensive tooling and complex forms are common. Truck hoods and fairing assemblies have been prevalent since the energy crisis in 1974.

Automotive Applications

The automotive industry has been slowly incorporating composite and FRP materials into cars to enhance efficiency, reliability and customer appeal. In 1960, the average car contained approximately 20 pounds of plastic material, while a car built in 1985 has on the average 245 pounds of plastic. Plastic materials are replacing steel in body panels, grills, bumpers and structural members. Besides traditional plastics, newer materials that are gaining acceptance include reinforced urethane, high heat distortion thermoplastics, high glass loaded polyesters, structural foams, super tough nylons, high molecular weight polyethylenes, high impact polypropylenes and polycarbonate blends. New processes are also accelerating the use of plastics in automobiles. These new processing technologies include reaction injection molding of urethane, compression molding, structural foam molding, blow molding, thermoplastic stamping, sheet molding, resin injection molding and resin transfer molding. [1-40]

Sheet molding compound (SMC) techniques using thermoset resins have evolved into an accepted method for producing functional and structural automotive parts. The dimensional stability of these parts, along with reduced tooling costs, lead to applications in the 1970s that were not necessarily performance driven. As Class A finishes were achieved, large exterior body panels made from SMC began to appear on production models. Today, structural applications are being considered as candidate applications for composites. Improvements in resin formulations and processing methods are being credited for more widespread applications. As an example, Ashland Composite Polymers has developed a more flexible SMC resin system in conjunction with the Budd Company, a leading U.S. producer of SMC body panels. Newer resins offer weight savings of 20% over conventional SMC methods and produce parts that are almost half the weight of steel (based on equal stiffness fender designs). [1-41]

MOBIK

The MOBIK company in Gerlingen, West Germany, is researching and developing advanced composite engineering concepts in the automotive industry. They believe that tomorrow's car must be economical and functional and more environmentally compatible. Composite Intensive Vehicles (CIVs) will weigh less and thus enable considerable savings in other areas. Lower horsepower engines, less assembly time and cost, longer life span and fewer repairs are among the benefits of composite intensive automobiles. In addition, these advanced composites will dampen noise and vibrations, allow for integration of parts, experience less corrosion, need less tooling and equipment transformation, and are recyclable. Obstacles they face include present lack of a high-speed manufacturing technology for advanced composites and new engineering solutions to overcome structural discontinuities. [1-42]

The April 1989 issue of *Plastics Technology* magazine reports that MOBIK has developed a high speed method for making advanced composite preforms for use in structural automotive components. The preforms are made from woven glass fabric and polyetherimide (PEI) thermoplastic. The method enables vacuum forming of 3 by 3 foot preforms in less than 30 seconds at about 20 psi. The method involves high speed fiber placement while the sheet is being thermoformed. MOBIK plans to produce prototype automotive preforms at a pilot plant scheduled to open this fall. Initial applications will also include preforms for aircraft interior cabins.

Ford

An example of new automotive structural applications for thermoset composites is Ford's crossmember pilot test program. The particular crossmember being studied supports 150 pounds of transmission weight and passes directly over the exhaust system, producing service temperatures in the 300°F to 400°F range. The prototype part was developed using 3 layers of braided triaxial E-glass with polyurethane resin over a polyurethane foam core. A slag wool pressboard with aluminum sheathing was molded into the part in the area of high heat exposure. The composite part ended up weighing 43% less than the steel part it replaced and had the added benefit of reducing noise, vibration and ride harshness (NVH). Although material costs are 85% higher, the 90 second overall cycle time achieved through process development should reduce costs with production rates of 250,000/year. [1-43]

Composite driveshafts are also being used in the automotive industry. During the 1985 Society of Plastics Industries (SPI) exhibit, Ford Motor Company won the transportation category with a graphite composite driveshaft for the 1985 Econoline van. The driveshaft was constructed of 20% carbon fiber and 40% E-glass fiber in a vinyl ester resin system. The shaft is totally corrosion resistant and weighs 61% less than the steel shaft it replaces. [1-40] Merlin Technologies and Celanese Corporation developed carbon/fiberglass composite driveshafts that, in addition to weight savings, offer reduced complexity, warranty savings, lower maintenance, cost savings, and noise and vibration reduction as compared to their metal counterparts. [1-24]

Another structural composite developmental program, initiated in 1981 by Ford Motor Company, focused on designing a composite rear floor pan for a Ford Escort model. Finite element models predicted that the composite part would not be as stiff but its strength would be double that of the identical steel part. The composite floor pan was made using fiberglass/vinyl ester sheet (SMC) and directionally reinforced sheet (XMC) molding compounds. Stock Escort components were used as fasteners. Ten steel components were consolidated into one composite molding, and a weight savings of 15% was achieved. A variety of static and dynamic material property tests were performed on the prototype, and all the specimens performed as had been predicted by the models. The structural integrity of the part was demonstrated, hence the feasibility of molding a large structural part using selective continuous reinforcements was shown. [1-45]

A sheet molding compound (SMC) material is used to make the tailgate of the Ford Bronco II and is also used in heavy truck cabs. [1-40] Ford utilizes a blow molded TPE air duct on its Escort automobiles. The front and rear bumper panels of Hyundai's Sonata are made from engineered blow molding (EBM). [1-46]

A study completed by Ford in 1988 confirms the feasibility of extensive plastics use as a means of reducing production costs for low volume automobiles, such as electric powered cars. According to the study, plastics yield a parts reduction ratio of 5:1, tooling costs are 60% lower than for steel stamping dies, adhesive bonding costs are 25-40% lower than welding, and structural composites demonstrate outstanding durability and crashworthiness. Composite front axle crossmember parts have undergone extensive testing in Detroit and await a rationale for production. [1-47]

The Ford Taurus and Mercury Sable cars utilize plastics extensively. Applications include exterior, interior and under the hood components, including grills, instrument panels and outside door handles, to roof trim panels and insulations, load floors, cooling fans and battery trays. The polycarbonate/PBT wraparound front and rear bumpers are injection molded of General Electric's Xenoy® material. [1-48]

Other significant new plastic applications in Ford vehicles include the introduction of the high density polyethylene fuel tank in the 1986 Aerostar van. [1-48]

A prototype graphite reinforced plastic vehicle was built in 1979 by Ford Motor Company. The project's objective was to demonstrate concept feasibility and identify items critical to production. The prototype car weighed 2,504 pounds, which was 1,246 pounds lighter than the same car manufactured of steel. Automotive engineers are beginning to realize the advantages of part integration, simplified production and reduced investment cost, in addition to weight savings and better durability. [1-40]

The Ford Motor Company in Redford, MI established engineering feasibility for the structural application of an HSMC Radiator Support, the primary concern being weight savings. [1-49] The Ford Motor Company and Dow Chemical Company combined efforts to design, build and test a structural composite crossmember/transverse leaf spring suspension module for a small van. Prototype parts were fabricated and evaluated in vehicle and laboratory tests, and results were encouraging. [1-50]

General Motors

Buick uses Hoechst Celanese's Riteflex® BP 9086 polyester elastomer alloy for the bumper fascia on its 1989 LeSabre for its paintability, performance and processability. [1-46]

The Pontiac Fiero has an all-plastic skin mounted on an all steel space frame. The space frame provides all the functional strengthening and stiffening and consists of a five-piece modular design, and the plastic body panels are for cosmetic appearance. The shifter trim plate for the Pontiac Fiero is made of molded styrene maleic anhydride (SMA) and resists warping and scratching, readily accepts paints and exceeds impact targets. Drive axle seals on the 1985 GM front wheel drive cars and trucks are made of Hytrel polyester elastomer for improved maintenance, performance and life. Wheel covers for the Pontiac Grand AM are molded of Vydyne mineral reinforced nylon for high temperature and impact resistance. [1-48]

GenCorp Automotive developed a low density sheet molding compound (SMC) that is claimed to be 30% lighter than standard SMC. The material has been introduced on the all-plastic bodied GM 200 minivan and the 1989 Corvette. [1-46] The automotive exterior panels on the

GM 200 APV minivan are plastic. The minivan has polyurea fenders and SMC skin for roofs, hoods and door panels. BMW also uses plastic exterior panels on its Z1 model. [1-51]

Chrysler

Chrysler undertook the Viper project in 1989 after the enthusiastic reaction to the concept car presented at the Automobile Show. With an extremely limited budget, steel body panels were out of the question. RTM panels were a likely choice, but required finishes coupled with thin sections were not being achieved at the time. Epoxy tools were produced to allow for mold modification in the first run of 300 cars. Initial RTM development concentrated on materials, which led to a resin that produced a Class A finish with zero shrinkage; 28% to 30% glass (mat and veils); and a gelcoat finish. For the higher production rates that ensued later in the project, SMC methods were used for body panels. For large parts, like the hood assembly, post curing at 250°F for one hour ensures mechanical property and dimensional stability. Highly stressed components, such as the transmission tunnel, are built with carbon and epoxy. [1-52]

In a joint program initiated in 1984 between the Shell Development Company, Houston, TX and the Chrysler Corporation, a composite version of the steel front crossmember for Chrysler's T-115 minivan was designed, fabricated and tested. Chrysler completed in-vehicle proving grounds testing in March 1987. The program increased confidence that composites made from non-exotic commercially available materials and fabrication processes can withstand severe service in structural automotive applications. [1-53]

Chrysler uses nearly 40 pounds of acrylonitrile-butadiene-styrene (ABS) in its single-piece, four-segment molded interior unit for the Dodge Caravan and Plymouth Voyager. [1-48]

Leafsprings

Research and testing has been performed by the University of Michigan on a composite elliptic spring, which was designed to replace steel coil springs used in current automobiles. The composite spring consists of a number of hollow elliptic elements joined together, as shown in Figure 1-42. The elliptic spring elements were manufactured by winding fiber reinforced epoxy tapes to various thicknesses over a collapsible mandrel. The work performed indicates that FRP springs have considerable potential as a substitute for steel coil springs. Among the advantages of the composite design are a weight savings of almost 50%, easier reparability, and the potential elimination of shock absorbers due to the high damping characteristics inherent in fiber reinforced plastics. [1-54]

Composite leafsprings for heavy trucks have been designed, manufactured and tested. In one program, a fiberglass sheet molding compound and epoxy resin were used with a steel main leaf in a compression-molding process. Mechanical testing of the finished parts demonstrated that design requirements for the component can be met using composites while achieving a minimum of 40% weight reduction over steel leafsprings. [1-55]

Frames

Graphite and Kevlar fibers with epoxy resin were used to make a composite heavy truck frame developed by the Convair Division of General Dynamics. The composite frame weighs 62% less than steel and has the same strength and stiffness. The frame was tested for one year (18,640 miles) on a GMC truck without any problems. No structural damage was evident, bolt holes maintained their integrity, and there was no significant creep of the resin matrix. [1-56]

A torsionally stiff, lightweight monocoque chassis was designed and fabricated in 1986 by the Vehicle Research Institute at Western Washington University, Bellingham, WA. Called the Viking VIII, this high performance, low cost sports car utilizes composite materials throughout and weighs only 1,420 pounds. Fiberglass, Kevlar® and carbon fiber were used with vinyl ester resin, epoxy adhesive and aluminum honeycomb core in various sandwich configurations. Final detailed test results were not available in the literature, however, most of the performance goals were met with the model. [1-57]

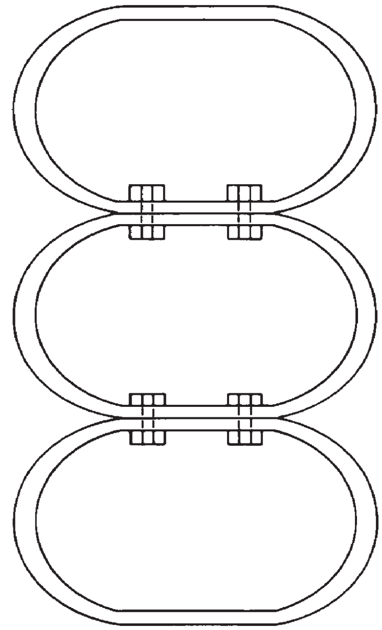


Figure 1-42 Composite Elliptic Spring [*ASM Engineers' Guide to Composite Materials*]

Safety Devices

Honeycomb structures can absorb a lot of mechanical energy without residual rebound and are particularly effective for cushioning air dropped supplies or instrument packages in missiles, providing earthquake damage restraints for above ground pipelines, or protecting people in rapid transit vehicles. A life-saving cushioning device called the Truck Mounted Crash Cushion (TMCC) has been used by the California Department of Motor Transportation. The TMCC has proven effective in preventing injury to, and saving the lives of, highway workers and motorists. The TMCC is mounted to slow moving or stopped transportation department maintenance and construction vehicles. In case of an accident, after an initial threshold stress (that can be eliminated by prestressing the honeycomb core) at which compressive failure begins, the core carries the crushing load at a controlled, near linear rate until it is completely dissipated without bouncing the impacting car or truck into a work crew or oncoming traffic.

Electric Cars

The promise of pollution reduction in the nation's cities through the utilization of electric vehicles (EV) relies in a large part in getting the vehicle weight down. In 1992, GM produced an all-composite electric car called the Ultralite. The body structure was hand laid up carbon/epoxy built by Scaled Composites and weighed half (420 pounds) of what a similar aluminum frame would weigh with twice the stiffness. Although material costs and manufacturing methods for this project were not realistic, it did prove the value of parts consolidation, weight reduction, corrosion resistance and styling latitude. [1-58]

Solectria has recently produced an all-composite sedan called the Sunrise built under Advanced Research Projects Agency (ARPA) funding. The company holds the EV range record of 238 miles on a single charge and has teamed up with composites manufacturer TPI and Dow-United Technologies (a Sikorski Aircraft spinnoff) for this effort. Dow-UT makes RTM parts for the aerospace industry and produces carbon composite parts for the Dodge Viper. [1-59]

Mass Transit

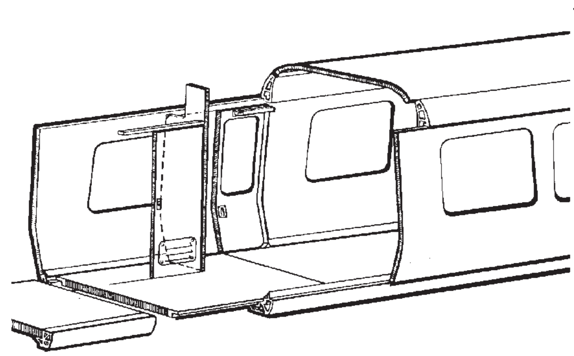


Figure 1-43 Applications of honeycomb panels in a passenger railcar application [Hexcel]

High speed passenger trains are in-service in Japan and France, but remain drawing board ideas in this country. Performance is gained, in part, through weight reduction and composite materials play an integral role with existing and proposed applications. Cored panels, consisting of either end-grain balsa or honeycomb structures, work best to resist the predominant out-of-plane loads. Skins are usually glass/phenolic or melamine. Spray-up glass/phenolic components are also utilized. In this country, people movers or monorail systems are in place at some amusement parks, at airports and in some downtown areas. The Walt Disney World monorail uses 800 pound car shells that are 95% glass/phenolic and 5% carbon/epoxy and are built by Advanced Technology & Research [1-60]

Cargo Handling

Shipping containers are now being constructed of FRP materials to achieve weight savings and to facilitate and simplify trans-shipment. Santa Fe Railway has developed an FRP container unit that is modular, allowing containers to be easily transferred to/from trucks, trains and ships. The containers are constructed using fiberglass in a polyester matrix with a core of balsa wood. The units are aerodynamically designed to reduce wind drag. The containers can be stacked up to six containers high when placed on a ship for transport. Aside from the substantial weight savings achieved using these containers, the transported goods need not be transferred from one form of container to another. This results in lower handling costs and reduces the risk of cargo damage. [1-61]

In 1992, Stoughton Composites took over Goldsworthy Engineering, a pioneer in pultrusion technology. They first introduced a refrigerated container for domestic use that was 1000 pounds lighter than aluminum versions and had 25% less heat transfer. Through a recent collaboration with American Presidential Lines and Kelly transportation, a standard 40-foot ISO container was developed for trans-ocean container ship use. The containers are made from E-glass/isopolyester pultruded panels up to 48" wide that incorporate (45° off-axis reinforcements. The container weighs 5,000 pounds as compared to 8,600 pound standard steel containers. Stoughton also anticipates the following advantages: no corrosion or painting requirements; adhesive bonding repairs versus welding or rivets; composite versus wood floors; 15-year life versu 8 - 10 years. [1-62]

Hardcore DuPont has teamed with Trinity and Burlington Northern to produce insulated railcars using their patented SCRIMP resin infusion process. The cars weigh 14,000 pounds each and are made with heavy knit E-glass fabrics from BTI and Dow's 411-350 vinyl ester resin. Like Stoughton's ISO containers, the prototype boxcars produced in mid-1995 show

15% weight reduction; 23% more capacity by weight and 13% more by volume; heat transfer estimated to be two-thirds of steel boxcars; and an estimated 50% reduction in maintenance costs. [1-63]

Manufacturing Technologies

Many competitive, stampable reinforced thermoplastic sheet products have been used during the past few years in the auto industry both in the U.S. and abroad. In 1988, Exxon Automotive Industry Sector, Farmington Hills, MI, introduced its Taffen STC (structural thermoplastic composite) stampable and compression-moldable sheet. This long-glass reinforced polypropylene sheet has already been used by European auto makers Peugeot, Audi, Vauxhall (GM) and Renault for instrument panel components, load floors, battery trays and other structural parts. A spokesman for Exxon claims that the material is under evaluation for 40 different programs at Ford, General Motors and Chrysler.

A North American automotive engineering company has been designing and testing blow molded fuel tanks for cars. Hedwin Corporation, West Bloomfield, MI recently announced the application of an all-HDPE blow molded fuel tank forward of the drive shaft. The tank was produced for the 1989 Ford Thunderbird and Mercury Cougar, and Hedwin claims it is the first in a U.S.-built car to be mounted forward of the drive shaft. Because of the tank's location, the design had to allow the shaft to pass through the middle of the tank, making it necessary to go to an exceedingly complex shape.

At the Spring 1989 Society of Automotive Engineers International Congress & Exposition, significant developments in quality-enhancing polymer systems and materials technology were demonstrated. General achievements include:

- Breakthroughs in high-productivity reaction injection molding (RIM) formulations and the equipment to handle them.
- Success for thermoplastic elastomer (TPE) fascia; with an ultra-soft thermoplastic styrenic-based product soon to emerge.
- Upgraded engineering and sound-damping foams for interior automotive and other specialty applications.
- More high-heat polyethylene terephthalate PET materials.
- A polyphenylene sulfide sulfone grade for underhood use.
- Long-steel-fiber reinforced resins designed for EMI shielding.
- Impact-modified polycarbonates, high-heat ABS grades, glass-reinforced acrylic-styrene-acrylonitrile/polybutylene terephthalate (ASA/PBT) blends, and impact acrylics.

Also at the Spring 1989 Exposition, Mobay Chemical Co. introduced a RIM polyurea formulation that is claimed to offer dramatic productivity gains, excellent thermal stability, a surface finish as smooth as steel, and good abrasion, corrosion and wear resistance. Mobay is building a facility at New Martinsville, WV to produce a patented amine-terminated polyether (ATPE) claimed to improve the quality of auto body panels and other components made with its polyurea systems. Mobay claims that its unreinforced STR-400 structural RIM (SRIM) system, which can be used for automotive applications such as bumper beams, trunk modules, truck boxes, spare-tire covers and roof caps, offers 50% greater notched Izod strength than its earlier grade of SRIM. [1-46]

Dow Chemical announced at the show its completion of the design and engineering of ultra high speed equipment to run the fast new RIM materials.

Proof of SRIM's practicality was seen on a bumper beam on the 1989 Corvette on display at the Dow exhibit. It is molded by Ardyne Inc., Grand Haven, MI, using Dow's Spectrim MM 310 system. The SRIM beam combines a directional and random glass preform with a matrix of thermosetting polycarbamate resin and saves 18% in weight and 14% in labor and material costs, according to Chevrolet.

Hercules announced two new SRIM systems at the Exposition. One, Grade 5000 is a SRIM system designed for glass reinforcement and intended for such uses as hoods, trunk lids, door panels, side fairings and fenders. The other, Grade 1537, is said to offer a higher heat deflection temperature (185°F) and better impact, stiffness and strength properties and is intended primarily for bumper covers, side fairing extensions, roof panels and sun visors. It is claimed to maintain ductility from -30° to 150°F. [1-46]

Materials

The following is a list of some promising material systems that have been introduced for automotive applications:

- Porsche uses Du Pont's Bexoly V thermoplastic polyester elastomer for the injection molded front and rear fascias on its new Carrera 4 model.
- Shell Chemical is introducing new styrenic-based Kraton elastomers, which are extremely soft with “excellent” compression set and moldability. Its applications in the transportation industry include window seals and weather gasketing, where softness, better than average heat resistance, and low compression set are important.
- A foam that debuted at the Spring 1989 Exposition is a cold curing flexible PUR from Mobay, which is designed to reduce noise levels inside automobiles. BMW now uses the foam system, called Bayfit SA, on all its models.
- General Electric Plastics has designed and developed a one-piece, structural thermoplastic, advanced instrument panel module, called AIM, for automobiles. The one-piece design sharply reduces production time. [1-46]
- Glass reinforced thermoplastic polyesters such as PBT (polybutylene terephthalate) are used extensively in the automotive industry for exterior body parts such as grilles, wheel covers and components for doors, windows and mirrors. PBT is also in demand for underhood applications such as distributor caps, rotors and ignition parts. Other uses include headlamp

parts, windshield wiper assemblies, and water pump and brake system components.

- Du Pont's Bexloy K 550 RPET has been accepted by Chrysler for use on fenders on some 1992 models. [1-64]
- The Polimotor/Lola T-616 is the world's first competition race car with a plastic engine. The four cylinder Polimotor engine is ⅔ plastic and contains dynamic parts of injection molded polymer supplied by Amoco Chemicals. The race car weighs 1500 pounds and has a carbon fiber chassis and body.
- Torlon® is a high performance polyamideimide thermoplastic made by Amoco. Torlon® has a very low coefficient of thermal expansion, which nearly matches that of steel and is stronger than many other types of high temperature polymers in its price range. It can be injection molded to precise detail with low unit cost. Torlon® thrust washers were incorporated into Cummins' gear-driven diesel engines starting in 1982. [1-48]

Industrial Use of FRP

Thermoplastic resins were first used for industrial applications in 1889. Reinforced polyester resins were first utilized in 1944. FRP's advantages in this field include: lightweight structural applications, wide useful temperature range, chemical resistance, flexibility, thermal and electrical insulation, and favorable fatigue characteristics.

Piping Systems

The use of FRP for large diameter industrial piping is attractive because handling and corrosion considerations are greatly improved. Filament wound piping can be used at working temperatures up to around 300^o F with a projected service life of 100 years. Interior surfaces are much smoother than steel or concrete, which reduces frictional losses. The major difficulty with FRP piping installation is associated with connection arrangements. Construction techniques and engineering considerations are presented here, along with specific application examples.

Pipe Construction

The cylindrical geometry of pipes make them extremely well suited for filament winding construction. In this process, individual lengths of fiberglass are wound on to a mandrel form in an engineered geometry. Resin is either applied at the time of winding or pre-impregnated (prepreg) into the fiberglass in a semi-cured state. High pressure pipes and tanks are fabricated using this technique.

A more economical but less structural method of producing pipes is called centrifugal casting. In this process, chopped glass fibers are mixed with resin and applied to the inside of a rotating cylindrical mold. The reinforcement fibers end up in a random arrangement making the structure's strength properties isotropic. This process is used for large diameter pipe in low pressure applications.

Contact molding by hand or with automated spray equipment is also used to produce large diameter pipe. The designer has somewhat more flexibility over directional strength properties with this process. Different applications may be more sensitive to either hoop stresses or longitudinal bending stresses. Figure 1-44 shows the typical construction sequence of a contact-molded pipe.

Piping Materials

Fiberglass is by far the most widely used reinforcement material for reinforced piping components. The strength benefits of higher strength fibers do not justify the added cost for large structures. The type of resin system used does vary greatly, depending upon the given application. Table 1-7 lists various resin characteristics with respect to pipe applications.

Engineering Considerations

The general approach to FRP pipe construction involves a chemically resistant inner layer that is surrounded by a high fiber content structural layer and finally a resin rich coating. Additional reinforcement is provided by ribbed stiffeners, which are either solid or hollow.

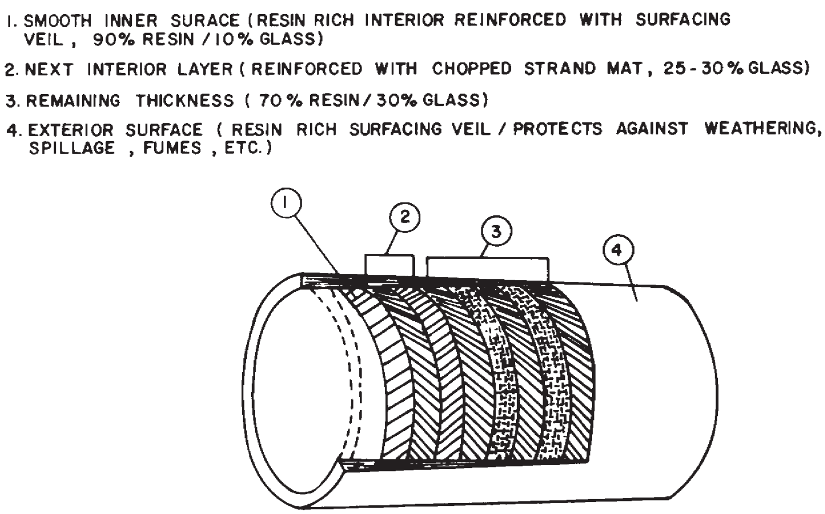


Figure 1-44 Cutaway View of Contact-Molded Pipe [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Table 1-7 FRP Pipe Resin Systems [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Resin	Application
Isophthalic	Mild corrosives at moderate temperatures and general acid wastes
Furmarated bi-sphenol A-type polyester	Mild to severe corrosive fluids including many alkalies and acids
Fire-retardant polyester	Maximum chemical resistance to acids, alkalies and solvents
Various thermoset resins	High degree of chemical resistance to specific chemicals
High-quality epoxy	Extremely high resistance to strong caustic solutions
Vinyl ester and proprietary resin systems	Extremely high resistance to organic acids, oxidizing acids, alkalis and specific solvents operating in excess of 350^{o}F

The joining of FRP pipe to other materials, such as steel, can be accomplished using a simple flange to flange mate; with an encased concrete system that utilizes thrust rings; or with a rubber expansion joint, as shown in Figure 1-45. For straight FRP connections, an “O ring” seal can be used.

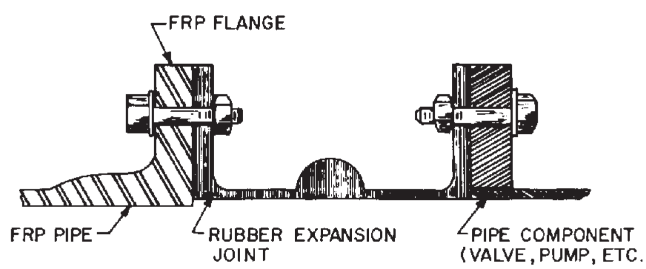


Figure 1-45 Typical Expansion Joint Tie-In [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook]*

Practices or codes regarding safe FRP pipe design are established by the following organizations:

- The American Society for Testing and Materials (ASTM);
- The American Society for Mechanical Engineers (ASME); and
- The American Petroleum Institute (API).

Table 1-8 presents average properties of FRP pipe manufactured by different methods. Table 1-9 lists some recommended wall thicknesses for filament wound and contact molded pipes.

FRP Piping Applications

Oil Industry

Approximately 500,000 feet of FRP pipe is installed at a Hodge-Union Texas project near Ringwood, OK, which is believed to be the single largest FRP pipe installation. FRP epoxy pipe was selected because of its excellent corrosion resistance and low paraffin buildup. The smoothness of the pipe walls and low thermal conductivity contribute to the inherent resistance to paraffin accumulation. The materials that tend to corrode metallic piping include crudes, natural gases, saltwater and corrosive soils. At an offshore installation in the Arabian Gulf, FRP vinyl ester pipe was selected because of its excellent resistance to saltwater and humidity. At this site, seawater is filtered through a series of 15 foot diameter tanks that are connected by 16 inch diameter piping using a multitude of FRP fittings.

Table 1-8 Average Properties of Various FRP Pipe
[Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Property	Filament Wound with Epoxy or Polyester Resins	Centrifugally Cast with Epoxy or Polyester Resin	Contact Molded with Polyester Resin
Modulus of Elasticity in Axial Tension @ 77° F, psi	$1.0 - 2.7 \times 10^6$	$1.3 - 1.5 \times 10^6$	$0.8 - 1.8 \times 10^6$
Ultimate Axial Tensile Strength @ 77° F, psi	8,000 - 10,000	25,000	9,000 - 18,000
Ultimate Hoop Tensile Strength @ 77° F, psi	24,000 - 50,000	35,000	9,000 - 10,000
Modulus of Elasticity in Beam Flexure @ 77° F, psi	$1 - 2 \times 10^6$	$1.3 - 1.5 \times 10^6$	$1.0 - 1.2 \times 10^6$
Coefficient of Thermal Expansion, inch/inch/°F	$8.5 - 12.7 \times 10^6$	13×10^6	15×10^6
Heat Deflection Temperature @ 264 psi, °F	200 - 300	200 - 300	200 - 250
Thermal Conductivity, Btu/ft^2-hr-°F/inch	1.3 - 2.0	0.9	1.5
Specific Gravity	1.8 - 1.9	1.58	1.3 - 1.7
Corrosive Resistance	E	E	NR

E = excellent, will resist most corrosive chemicals
NR = not recommended for highly alkaline or solvent applications

Coal Mine

Coal mines have successfully used FRP epoxy resin pipe, according to the Fiber Glass Resources Corporation. The material is capable of handling freshwater, acid mine water and slurries more effectively than mild steel and considerably cheaper than stainless steel. Additionally, FRP is well suited for remote areas, fire protection lines, boreholes and rough terrain installations.

Paper Mill

A paper mill in Wisconsin was experiencing a problem with large concentrations of sodium hydroxide that was a byproduct of the deinking process. Type 316 stainless steel was replaced with a corrosion resistant FRP using bell and spigot-joining methods to further reduce installation costs.

Power Production

Circulating water pipes of 96 inch diameter FRP were specially designed to meet the engineering challenges of the ***Big Cajun #2*** fossil fuel power plant in New Roads, LA. The instability of the soil precluded the use of conventional thrust blocks to absorb axial loads. By custom lay-up of axial fiber, the pipe itself was made to handle these loads. Additionally, custom elbow joints were engineered to improve flow characteristics in tight turns.

Table 1-9 Recommended FRP Pipe Wall Thickness in Inches
[Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook*]

Inside Diam, Inches	Internal Pressure Rating, psi											
	25		50		75		100		125		150	
	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded	Filament Wound	Contact Molded
2	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.187
4	0.188	0.187	0.188	0.187	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.250
6	0.188	0.187	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.312	0.188	0.375
8	0.188	0.187	0.188	0.250	0.188	0.250	0.188	0.312	0.188	0.375	0.188	0.437
10	0.188	0.187	0.188	0.250	0.188	0.312	0.188	0.375	0.188	0.437	0.188	0.500
12	0.188	0.187	0.188	0.250	0.188	0.375	0.188	0.437	0.188	0.500	0.214	0.625
18	0.188	0.250	0.188	0.375	0.188	0.500	0.214	0.625	0.268	0.750	0.321	0.937
24	0.188	0.250	0.188	0.437	0.214	0.625	0.286	0.812	0.357	1.000	0.429	1.120
36	0.188	0.375	0.214	0.625	0.321	0.937	0.429	1.250	0.536	1.500	0.643	1.810
48	0.188	0.437	0.286	0.812	0.429	1.250	0.571	1.620	0.714	2.000	0.857	2.440
60	0.188	0.500	0.357	1.000	0.536	1.500	0.714	2.000	0.893	2.500	1.070	3.000
72	0.214	0.625	0.429	1.250	0.643	1.810	0.857	2.440	1.070	3.000	1.290	3.620
96	0.286	0.812	0.571	1.620	0.857	2.440	1.140	3.250	1.430	4.000	1.710	4.810

Tanks

FRP storage tanks are gaining increased attention as of late due to recent revelations that their metallic counterparts are corroding and rupturing in underground installations. The fact that this activity can go unnoticed for some time can lead to severe environmental ramifications.

Construction

A cross-sectional view of a typical FRP tank would closely resemble the pipe described in the previous section with a barrier inner skin followed by the primary reinforcing element. Figure 1-46 shows the typical construction of an FRP tank. A general limit for design strain level is 0.001 $^{inch}/_{inch}$ according to ASTM for filament wound tanks and National Institute of Standards and Technology (NIST) for contact molded tanks. Hoop tensile modulii (psi) range from 2.0 x 10^6 to 4.3 x 10^6 for filament winding and 1.0 x 10^6 to 1.2 x 10^6 for contact molding.

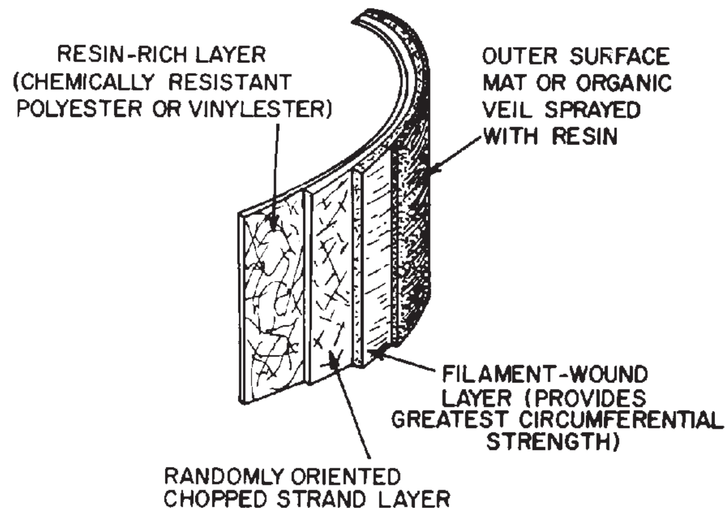


Figure 1-46 Cross-Sectional View of Standard Vertical Tank Wall Laminate [Cheremisinoff, *Fiberglass-Reinforced Plastics Deskbook]*

Application

FRP is used for vertical tanks when the material to be stored creates a corrosion problem for conventional steel tanks. Designs vary primarily in the bottom sections to meet drainage and strength requirements. Horizontal tanks are usually used for underground storage of fuel oils. Owens-Corning has fabricated 48,000 gallon tanks for this purpose that require no heating provision when buried below the frost line.

Air Handling Equipment

FRP blower fans offer protection against corrosive fumes and gases. The ease of moldability associated with FRP fan blades enables the designer to specify an optimum shape. An overall reduction in component weight makes installation easier. In addition to axial fans, various types of centrifugal fans are fabricated of FRP.

Ductwork and stacks are also fabricated of FRP when corrosion resistance and installation ease are of paramount concern. Stacks are generally fabricated using hand lay-up techniques employing some type of fire-retardant resin.

Commercial Ladders

The Fiber Technology Corporation is an example of a company that has adapted an aluminum ladder design for a customer to produce a nonconductive FRP replacement. The intricate angles and flares incorporated into the aluminum design precluded the use of a pultrusion process. Additionally, the design incorporated unique hinges to give the ladder added versatility. All these features were maintained while the objective of producing a lighter, nonconductive alternative was achieved.

Major ladder manufacturers, such as R.D. Werner and Lynn Manufacturing also produce step and extension type ladders using rails made from pultruded glass/polyester structural sections. Indeed, ANSI has developed standard A 14.5-1982 for ladders of portable reinforced plastics. Table 1-10 lists the minimum mechanical properties required for compliance with the ANSI standard.

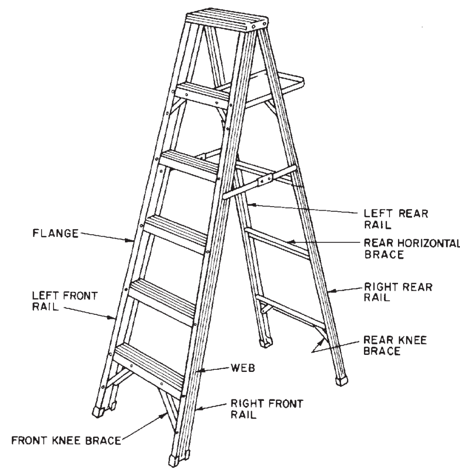


Figure 1-47 Stepladder with Composite Rails [ANSI standard A14.5-1982]

Table 1-10 Minimum Composite Properties of Ladder Rail Sections [American National Standards Institute standard A14.5-1982]

Material Property	Flange	Web	Web	Web Lengthwise		
	Lengthwise		Cross	Wet	150°F	Weather
Tensile Strength, psi	45,000	30,000	-	23,000	21,000	23,000
Tensile Modulus, 10^6 psi	2.8	2.0	-	1.5	1.4	1.5
Compressive Strength, psi	40,000	28,000	10,000	21,000	19,000	22,000
Compressive Modulus, 10^6 psi	2.8	2.0	-	1.5	1.4	1.6
Flexural Strength, psi	38,000	35,000	5,000	26,000	26,000	28,000
Flexural Modulus, 10^6 psi	2.0	1.8	0.70	1.4	1.4	1.4
Ultimate Bearing Strength, psi	-	30,000	-	-	-	-
Izod Impact, ft-lb/inch	-	20	-	-	-	-

Aerial Towers

In 1959, the Plastic Composites Corporation introduced an aerial man-lift device used by electrical and telephone industries. The bucket, upper boom and lower boom insulator are all fabricated of fiberglass. The towers, known today as “cherry pickers,” are currently certified to 69 kVA in accordance with ANSI standards and are periodically verified for structural integrity using acoustic emission techniques.

Drive Shafts

Power transmission drive shafts have been built from composite materials for over a decade. Initial applications focused on high corrosivity areas, such as cooling towers. As end fitting and coupling mechanisms developed, other benefits of composites have been realized. Addax, Inc. has built over 1700 shafts up to 255 inches long with power transmission to 4,500 hp. Figure 1-48 shows a flexible composite coupling patented by Addax that allows for misalignment. Industrial drive shafts that weigh 500 pounds when made from metal can weigh as little as 100 pounds when built with carbon/epoxy. [1-65]

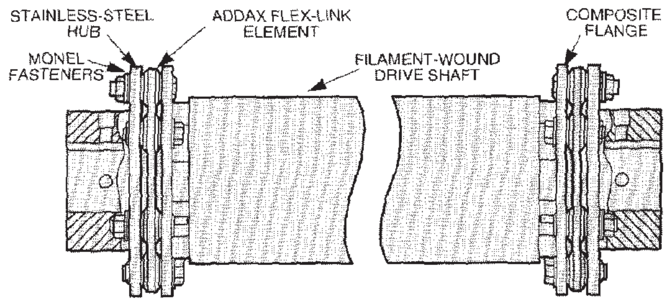


Figure 1-48 Patented Flexible Coupling Allows for up to 2° Misalignment [Addax]

Bridge Structures

Several recent projects headed by universities have focused on applying composite materials for infrastructure applications. The University of California, San Diego undertook an ARPA effort that focused on renewal and new structures. The higher profile tasks included: wrapping deteriorated and seismic-prone concrete columns; manufacture and analysis of bridge decks; cable and anchoring technology; and development of composite wear surfaces.

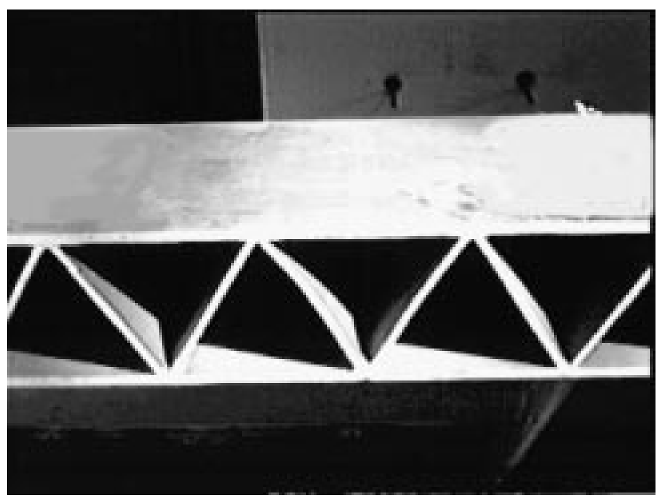


Figure 1-49 Early Prototype Truss Structure Built by Hardcore DuPont and Tested at UCSD [author photo]

Wrapping concrete columns with helical reinforcement is being approached differently by several companies. XXsys Technologies developed a wrapping machine that applies carbon/epoxy prepreg in a continuous fashion. Hexcell Fyfe uses a glass/epoxy system known as Tyfo S Fibrwrap^{tm}, which is applied by hand wrapping. Both NCF Industries and Hardcore DuPont utilize a technique where prefabricated shells are fit around columns and bonded in-place. ClockSpring uses a continuous prepreg wound around columns in a process borrowed from the offshore oil industry for heating large pipes. [1-66]

Aerospace Composites

The use of composites in the aerospace industry has increased dramatically since the 1970s. Traditional materials for aircraft construction include aluminum, steel and titanium. The primary benefits that composite components can offer are reduced weight and assembly simplification. The performance advantages associated with reducing the weight of aircraft structural elements has been the major impetus for military aviation composites development. Although commercial carriers have increasingly been concerned with fuel economy, the potential for reduced production and maintenance costs has proven to be a major factor in the push towards composites. Composites are also being used increasingly as replacements for metal parts on older planes. Figure 1-50 shows current and projected expenditures for advanced composite materials in the aerospace industry.

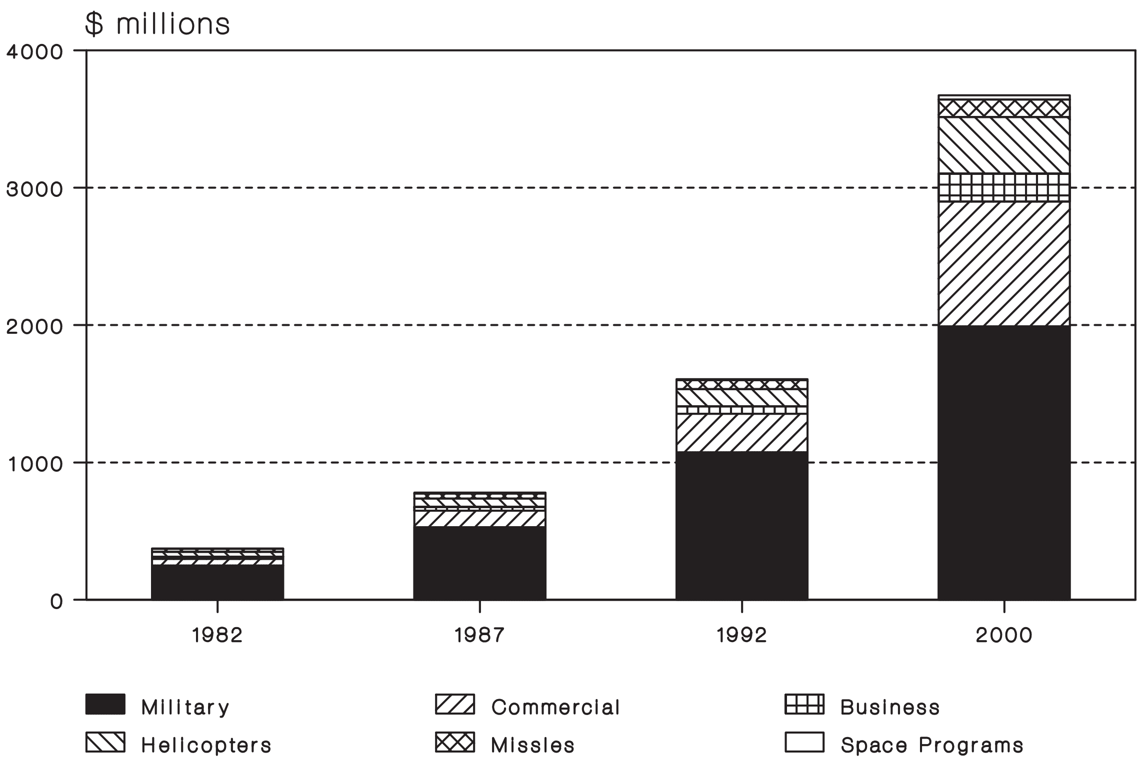


Figure 1-50 Advanced Composite Sales for the Aerospace Industry. [Source: *P-023N Advanced Polymer Matrix Composites*, Business Communication Company, Inc.]

When comparing aerospace composites development to that of the marine industry, it is important to note the differences in economic and engineering philosophies. The research, design and testing resources available to the aerospace designer eclipse what is available to his counterpart in the marine industry by at least an order of magnitude. Aircraft development remains one of the last bastions of U.S. supremacy, which accounts for its broad economic base of support. On the engineering side, performance benefits are much more significant for aircraft than ships. A comparison of overall vehicle weights provides a good illustration of this concept.

Although the two industries are so vastly different, lessons can be learned from aircraft development programs that are applicable to marine structures. Material and process development, design methodologies, qualification programs and long-term performance are some of the fields where the marine designer can adapt the experience that the aerospace industry has developed. New aircraft utilize what would be considered high performance composites in marine terms. These include carbon, boron and aramid fibers combined with epoxy resins. Such materials have replaced fiberglass reinforcements, which are still the backbone of the marine industry. However, structural integrity, producibility and performance at elevated temperatures are some concerns common to both industries. Examples of specific aerospace composites development programs are provided to illustrate the direction of this industry.

Business and Commercial

Lear Fan 2100

As one of the first aircraft conceived and engineered as a "composites" craft, the Lear Fan uses approximately 1880 pounds of carbon, glass and aramid fiber material. In addition to composite elements that are common to other aircraft, such as doors, control surfaces, fairings and wing boxes, the Lear Fan has an all-composite body and propeller blades.

Beech Starship

The Starship is the first all-composite airplane to receive FAA certification. Approximately 3000 pounds of composites are used on each aircraft.

Boeing

The Boeing 757 and 767 employ about 3000 pounds each of composites for doors and control surfaces. The 767 rudder at 36 feet is the largest commercial component in service. The 737-300 uses approximately 1500 pounds of composites, which represents about 3% of the overall structural weight. Composites are widely used in aircraft interiors to create luggage compartments, sidewalls, floors, ceilings, galleys, cargo liners and bulkheads. Fiberglass with epoxy or phenolic resin utilizing honeycomb sandwich construction gives the designer freedom to create aesthetically pleasing structures while meeting flammability and impact resistance requirements.

Airbus

In 1979, a pilot project was started to manufacture carbon fiber fin box assemblies for the A300/A310 aircraft. A highly mechanized production process was established to determine if high material cost could be offset by increased manufacturing efficiency. Although material costs were 35% greater than a comparable aluminum structure, total manufacturing costs were lowered 65 to 85%. Robotic assemblies were developed to handle and process materials in an optimal and repeatable fashion.

Military

Advanced Tactical Fighter (ATF)

Advanced composites enable the ATF to meet improved performance requirements such as reduced drag, low radar observability and increased resistance to temperatures generated at high speeds. The ATF will be approximately 50% composites by weight using DuPont's Avimid K polyamide for the first prototype. Figure 1-51 depicts a proposed wing composition as developed by McDonnell Aircraft through their Composite Flight Wing Program.

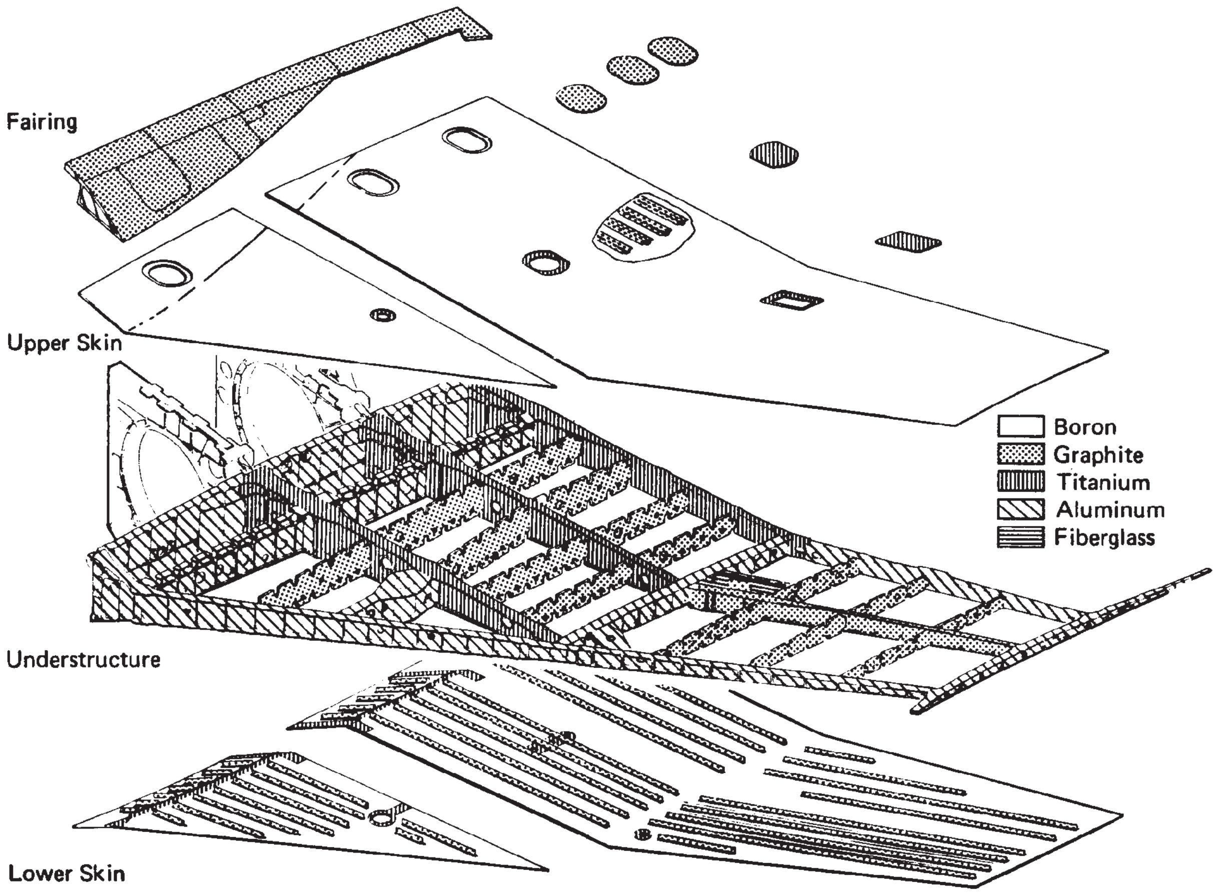


Figure 1-51 Composite Wing Composition for Advanced Tactical Fighter [Moors, *Design Considerations - Composite Flight Wing Program*]

Advanced Technology Bomber (B-2)

The B-2 derives much of its stealth qualities from the material properties of composites and their ability to be molded into complex shapes. Each B-2 contains an estimated 40,000 to 50,000 pounds of advanced composite materials. According to Northrop, nearly 900 new materials and processes were developed for the plane.

Second Generation British Harrier "Jump Jet" (AV-8B)

This vertical take-off and landing (VTOL) aircraft is very sensitive to overall weight. As a result, 26% of the vehicle is fabricated of composite material. Much of the substructure is composite, including the entire wing. Bismaleimides (BMI's) are used on the aircraft's underside and wing trailing edges to withstand the high temperatures generated during take-off and landing.

Navy Fighter Aircraft (F-18A)

The wing skins of the F-18A represented the first widespread use of graphite/epoxy in a production aircraft. The skins vary in thickness up to one inch, serving as primary as well as secondary load carrying members. It is interesting to note that the graphite skins are separated from the aluminum framing with a fiberglass barrier to prevent galvanic corrosion. The carrier- based environment that Navy aircraft are subjected to has presented unique problems to the aerospace designer. Corrosion from salt water surroundings is exacerbated by the sulfur emission from the ship's exhaust stacks.

Osprey Tilt-Rotor (V-22)

The tilt-rotor V-22 is also a weight sensitive craft that is currently being developed by Boeing and Bell Helicopter. Up to 40% of the airframe consists of composites, mostly AS-4 and IM-6 graphite fibers in 3501-6 epoxy (both from Hercules). New uses of composites are being exploited on this vehicle, such as shafting and thick, heavily loaded components. Consequently, higher design strain values are being utilized.

Helicopters

Rotors

Composite materials have been used for helicopter rotors for some time now and have gained virtually 100% acceptance as the material of choice. The use of fibrous composites offers improvements in helicopter rotors due to improved aerodynamic geometry, improved aerodynamic tuning, good damage tolerance and potential low cost. Anisotrophic strength properties are very desirable for the long, narrow foils. Additionally, a cored structure has the provision to incorporate the required balance weight at the leading edge. The favorable structural properties of the mostly fiberglass foils allow for increased lift and speed. Fatigue characteristics of the composite blade are considerably better than their aluminum counterparts with the aluminum failing near 40,000 cycles and the composite blade exceeding 500,000 cycles without failure. Vibratory strain in this same testing program was $\pm$ 510 $\mu\,{}^{inch}/_{inch}$ for aluminum and $\pm$ 2400 $\mu\,{}^{inch}/_{inch}$ for the composite.

Sikorsky Aircraft of United Aircraft Corporation has proposed a Cross Beam Rotor (XBR)™, which is a simplified, lightweight system that makes extensive use of composites. The low torsional stiffness of a unidirectional composite spar allows pitch change motion to be accommodated by elastic deformation, whereas sufficient bending stiffness prevents areoelastic instability. Figure 1-52 shows a configuration for a twin beam composite blade used with this system.

Structure and Components

The extreme vibratory environment that helicopters operate in makes composites look attractive for other elements. In an experimental program that Boeing undertook, 11,000 metal parts were replaced by 1,500 composite ones, thus eliminating 90% of the vehicle's fasteners. Producibility and maintenance considerations improved along with overall structural reliability.

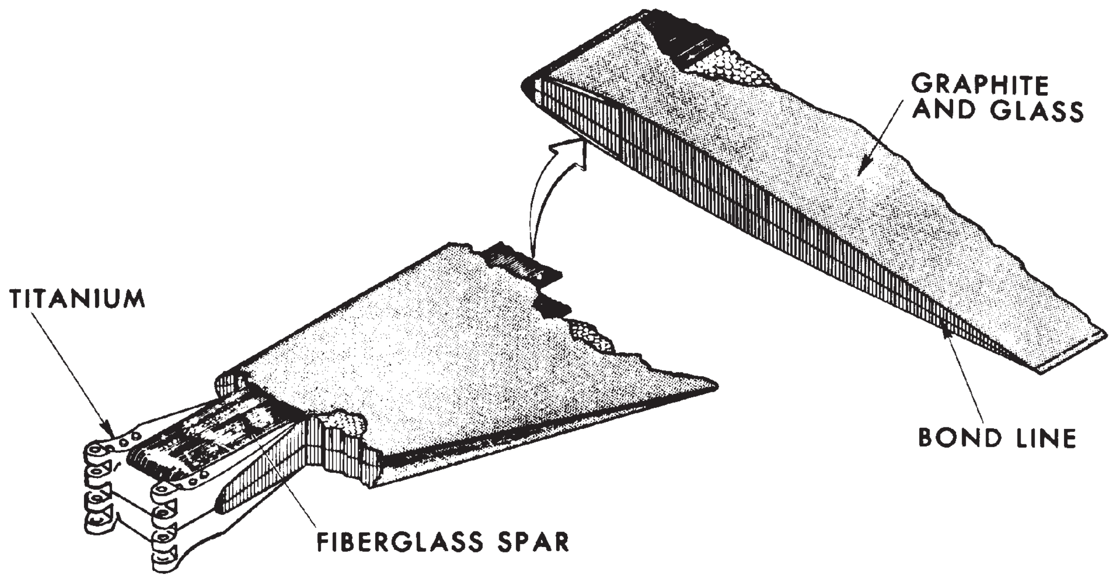


Figure 1-52 Twin Beam Composite Blade for XBR™ Helicopter Rotor System [Salkind, *New Composite Helicopter Rotor Concepts*]

Experimental

Voyager

Nearly 90% of the *VOYAGER* aircraft was made of carbon fiber composites. The strength-to-weight ratio of this material allowed the vehicle to carry sufficient fuel to circle the globe without refueling. The plane's designer and builder, Burt Rutan, is renowned for building innovative aircraft using composites. He has also designed an Advanced Technology Tactical Transport of composites and built the wing sail that was fitted to the 60 foot catamaran used in the last America's Cup defense.

Daedalus

The *GOSSAMER CONDOR* and *GOSSAMER ALBATROSS* caught people's imagination by being the first two human-powered aircraft to capture prize money that was unclaimed for 18 years. These aircraft were constructed of aluminum tubes and mylar wings supported by steel cable. The aerodynamic drag of the cabling proved to be the factor limiting flight endurance. The *DAEDALUS* project's goal was to fly 72 miles from Crete to Santorini. By hand constructing graphite spars over aluminum mandrels, the vehicle's drag was minimized and the overall aircraft structure was reduced to 68 pounds, which made this endurance record possible.

Composite Materials

Materials form an integral part of the way composite structures perform. Because the builder is creating a structural material from diverse constituent compounds, material science concepts are essential to the understanding of how structural composites behave. This chapter encompasses three broad groups of composite materials:

- Reinforcements;
- Resins; and
- Core Materials.

Descriptions and physical property data of representative marine materials will be presented. As with all composite material system design, the reader is cautioned not to optimize materials from each group without regard for how a system will perform as a whole. Material suppliers are often a good source of information regarding compatibility with other materials.

Reinforcements for marine composite structures are primarily E-glass due to its cost for strength and workability characteristics. In contrast, the aerospace industry relies on carbon fiber as it's backbone. In general, carbon, aramid fibers and other specialty reinforcements are used in the marine field where structures are highly engineered for optimum efficiency. Architecture and fabric finishes are also critical elements of correct reinforcement selection.

Resin systems are probably the hardest material group for the designer and builder to understand. Fortunately, chemists have been working on formulations since Bakelite in 1905. Although development of new formulations is ongoing, the marine industry has generally based its structures on polyester resin, with trends to vinyl ester and epoxy for structurally demanding projects and highly engineered products. A particular resin system is effected by formulation, additives, catylization and cure conditions. Characteristics of a cured resin system as a structural matrix of a composite material system is therefore somewhat problematic. However certain quantitative and qualitative data about available resin systems exists and is given with the caveat that this is the most important fabrication variable to be verified by the “build and test” method.

Core materials form the basis for sandwich composite structures, which clearly have advantages in marine construction. A core is any material that can physically separate strong, laminated skins and transmit shearing forces across the sandwich. Core materials range from natural species, such as balsa and plywood, to highly engineered honeycomb or foam structures. The dynamic behavior of a composite structure is integrally related to the characteristics of the core material used.

Reinforcement Materials

Fiberglass

Glass fibers account for over 90% of the fibers used in reinforced plastics because they are inexpensive to produce and have relatively good strength to weight characteristics. Additionally, glass fibers exhibit good chemical resistance and processability. The excellent tensile strength of glass fibers, however, may deteriorate when loads are applied for long periods of time. [2-1] Continuous glass fibers are formed by extruding molten glass to filament diameters between 5 and 25 micrometers. Table 2-1 depicts the designations of fiber diameters commonly used in the FRP industry.

Table 2-1 Glass Fiber Diameter Designations [Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Designation	Mils	Micrometers (10^{-6} meters)
C	0.18	4.57
D	0.23	5.84
DE	0.25	6.35
E	0.28	7.11
G	0.38	9.65
H	0.42	10.57
K	0.53	13.46

Individual filaments are coated with a sizing to reduce abrasion and then combined into a strand of either 102 or 204 filaments. The sizing acts as a coupling agent during resin impregnation. Table 2-2 lists the composition by weight for both E- and S-glass. Table 2-3 lists some typical glass finishes and their compatible resin systems. E-glass (lime aluminum borosilicate) is the most common reinforcement used in marine laminates because of its good strength properties and resistance to water degradation. S-glass (silicon dioxide, aluminum and magnesium oxides) exhibits about one third better tensile strength, and in general, demonstrates better fatigue resistance. The cost for this variety of glass fiber is about three to four times that of E-glass. Table 2-4 contains data on raw E-glass and S-glass fibers.

Table 2-2 Glass Composition by Weight for E- and S-Glass [BGF]

	E-Glass	S-Glass
Silicone Dioxide	52 - 56%	64 - 66%
Calcium Oxide	16 - 25%	0 - .3%
Aluminum Oxide	12 - 16%	24 - 26%
Boron Oxide	5 - 10%	—
Sodium & Potassium Oxide	0 - 2%	0 - .3%
Magnesium Oxide	0 - 5%	9 - 11%
Iron Oxide	.05 - .4%	0 - .3%
Titanium Oxide	0 - .8%	—
Fluorides	0 - 1.0%	—

Polymer Fibers

The most common aramid fiber is Kevlar® developed by DuPont. This is the predominant organic reinforcing fiber, whose use dates to the early 1970s as a replacement for steel belting in tires. The outstanding features of aramids are low weight, high tensile strength and modulus, impact and fatigue resistance, and weaveability. Compressive performance of aramids is not as good as glass, as they show nonlinear ductile behavior at low strain values. Water absorption of un-impregnated Kevlar® 49 is greater than other reinforcements, although ultra-high modulus Kevlar® 149 absorbs almost two thirds less than Kevlar® 49. The unique characteristics of aramids can best be exploited if appropriate weave style and handling techniques are used.

Table 2-3 Resin Compatibility of Typical Glass Finishes [BGF, Shell, SP Systems and Wills]

Designation	Type of Finish	Resin System
Volan® A	Methacrylato chromic chloride	Polyester, Vinyl Ester or Epoxy
Garan	Vinyl silane	Epoxy
NOL-24	Halosilane (in xylene)	Epoxy
114	Methacrylato chromic chloride	Epoxy
161	Soft, clear with good wet-out	Polyester or Vinyl Ester
504	Volan® finish with .03%-.06% chrome	Polyester, Vinyl Ester or Epoxy
504A	Volan® finish with .06%-.07% chrome	Polyester, Vinyl Ester or Epoxy
538	A-1100 amino silane plus glycerine	Epoxy
550	Modified Volan®	Polyester or Vinyl Ester
558	Epoxy-functional silane	Epoxy
627	Silane replacement for Volan®	Polyester, Vinyl Ester or Epoxy
630	Methacrylate	Polyester or Vinyl Ester
A-100	Amino silane	Epoxy
A-172	Vinyl	Polyester or Vinyl Ester
A-174	Vinyl	Polyester or Vinyl Ester
A-187	Epoxy silane	Epoxy
A-1100	Amino silane	Epoxy or Phenolic
A-1106	Amino silane	Phenolic
A-1160	Ureido	Phenolic
S-553	Proprietary	Epoxy
S-920	Proprietary	Epoxy
S-735	Proprietary	Epoxy
SP 550	Proprietary	Polyester, Vinyl Ester or Epoxy
Y-2967	Amino silane	Epoxy
Y-4086/7	Epoxy-modified methoxy silane	Epoxy
Z-6030	Methacrylate silane	Polyester or Vinyl Ester
Z-6032	Organo silane	Epoxy
Z-6040	Epoxy-modified methoxy silane	Epoxy

Allied Corporation developed a high strength/modulus extended chain polyethylene fiber called Spectra® that was introduced in 1985. Room temperature specific mechanical properties of Spectra® are slightly better than Kevlar®, although performance at elevated temperatures falls off. Chemical and wear resistance data is superior to the aramids. Data for both Kevlar® and Spectra® fibers is also contained in Table 2-4. The percent of manufacturers using various reinforcement materials is represented in Figure 2-1.

Table 2-4 Mechanical Properties of Reinforcement Fibers

Fiber	Density lb/in^3	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^6	Ultimate Elongation	Cost $/lb
E-Glass	.094	500	10.5	4.8%	.80-1.20
S-Glass	.090	665	12.6	5.7%	4
Aramid-Kevlar® 49	.052	525	18.0	2.9%	16
Spectra® 900	.035	375	17.0	3.5%	22
Polyester-COMPET®	.049	150	1.4	22.0%	1.75
Carbon-PAN	.062-.065	350-700	33-57	0.38-2.0%	17-450

Polyester and nylon thermoplastic fibers have recently been introduced to the marine industry as primary reinforcements and in a hybrid arrangement with fiberglass. Allied Corporation has developed a fiber called COMPET®, which is the product of applying a finish to PET fibers that enhances matrix adhesion properties. Hoechst-Celanese manufactures a product called Treveria®, which is a heat treated polyester fiber fabric designed as a "bulking" material and as a gel coat barrier to reduce "print-through." Although polyester fibers have fairly high strengths, their stiffness is considerably below that of glass. Other attractive features include low density, reasonable cost, good impact and fatigue resistance, and potential for vibration damping and blister resistance.

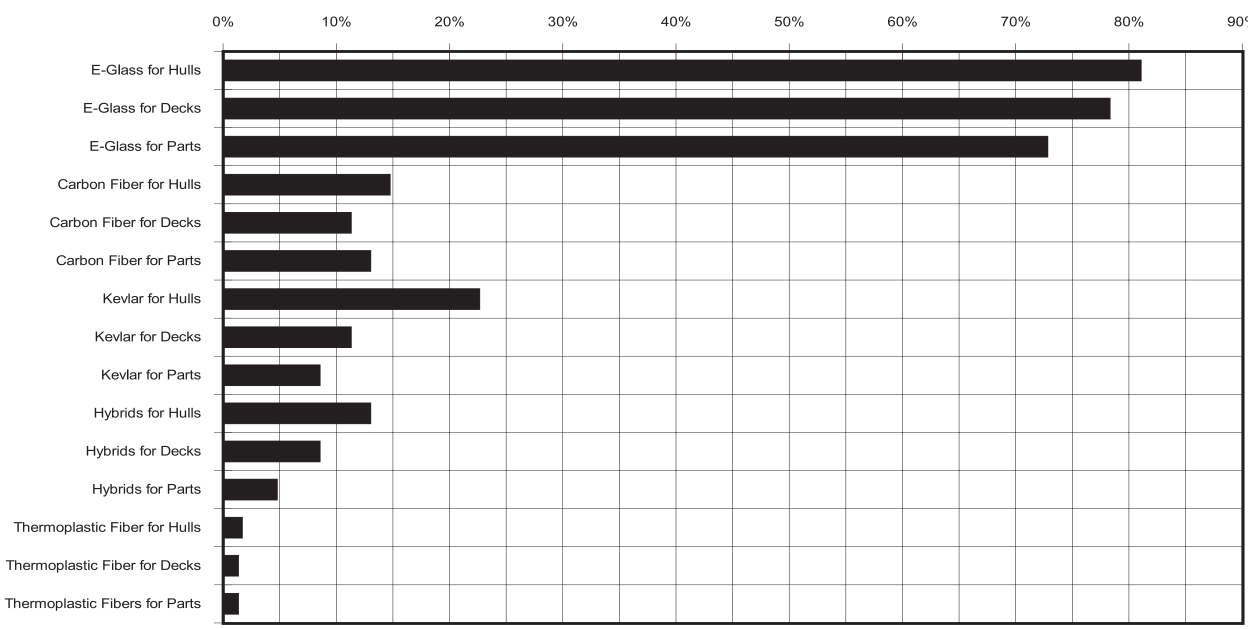


Figure 2-1 Marine Industry Reinforcement Material Use [EGA Survey]

Carbon Fibers

The terms "carbon" and "graphite" fibers are typically used interchangeably, although graphite technically refers to fibers that are greater than 99% carbon composition versus 93 to 95% for PAN-base fibers. All continuous carbon fibers produced to date are made from organic precursors, which in addition to PAN (polyacrylonitrile), include rayon and pitches, with the latter two generally used for low modulus fibers.

Carbon fibers offer the highest strength and stiffness of all commonly used reinforcement fibers. The fibers are not subject to stress rupture or stress corrosion, as with glass and aramids. High temperature performance is particularly outstanding. The major drawback to the PAN-base fibers is their relative cost, which is a function of high precursor costs and an energy intensive manufacturing process. Table 2-4 shows some comparative fiber performance data.

Reinforcement Construction

Reinforcement materials are combined with resin systems in a variety of forms to create structural laminates. The percent of manufacturers using various reinforcement styles is represented in Figure 2-5. Table 2-5 provides definitions for the various forms of reinforcement materials. Some of the lower strength non-continous configurations are limited to fiberglass due to processing and economic considerations.

Table 2-5 Description of Various Forms of Reinforcements [Shell, *Epon® Resins for Fiberglass Reinforced Plastics*]

Form	Description	Principal Processes
Filaments	Fibers as initially drawn	Processed further before use
Continuous Strands	Basic filaments gathered together in continuous bundles	Processed further before use
Yarns	Twisted strands (treated with after-finish)	Processed further before use
Chopped Strands	Strands chopped ¼ to 2 inches	Injection molding; matched die
Rovings	Strands bundled together like rope but not twisted	Filament winding; sheet molding; spray-up; pultrusion
Milled Fibers	Continuous strands hammermilled into short lengths 1/32 to ⅛ inches long	Compounding; casting; reinforced reaction injection molding (RRIM)
Reinforcing Mats	Nonwoven random matting consisting of continuous or chopped strands	Hand lay-up; resin transfer molding (RTM); centrifugal casting
Woven Fabric	Cloth woven from yarns	Hand lay-up; prepreg
Woven Roving	Strands woven like fabric but coarser and heavier	Hand or machine lay-up; resin transfer molding (RTM)
Spun Roving	Continuous single strand looped on itself many times and held with a twist	Processed further before use
Nonwoven Fabrics	Similar to matting but made with unidirectional rovings in sheet form	Hand or machine lay-up; resin transfer molding (RTM)
Surfacing Mats	Random mat of monofilaments	Hand lay-up; die molding; pultrusion

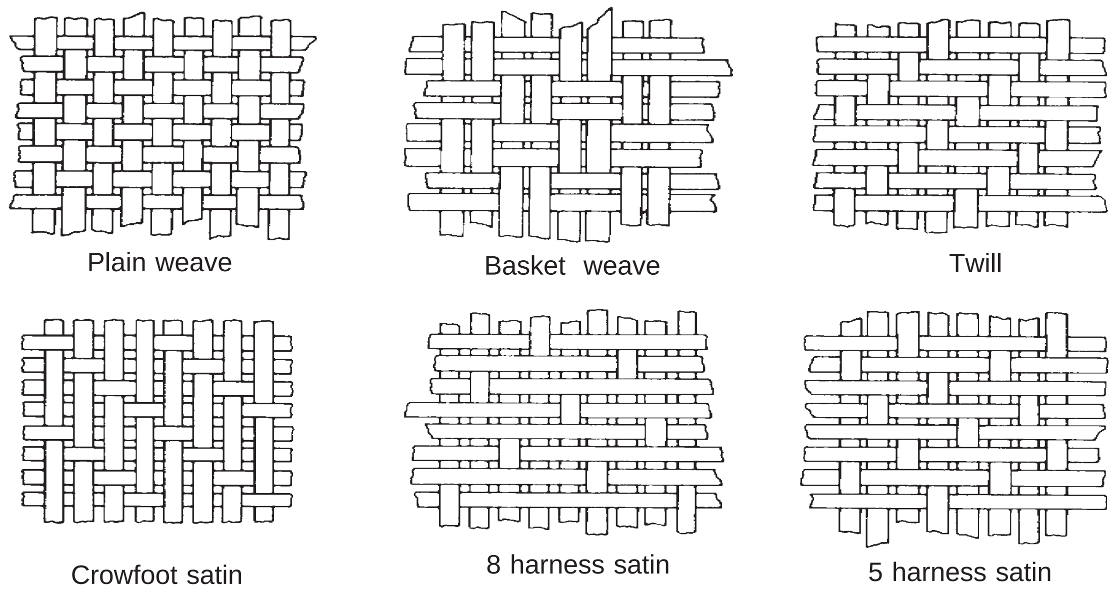


Figure 2-2 Reinforcement Fabric Construction Variations [*ASM Engineered Materials Handbook*]

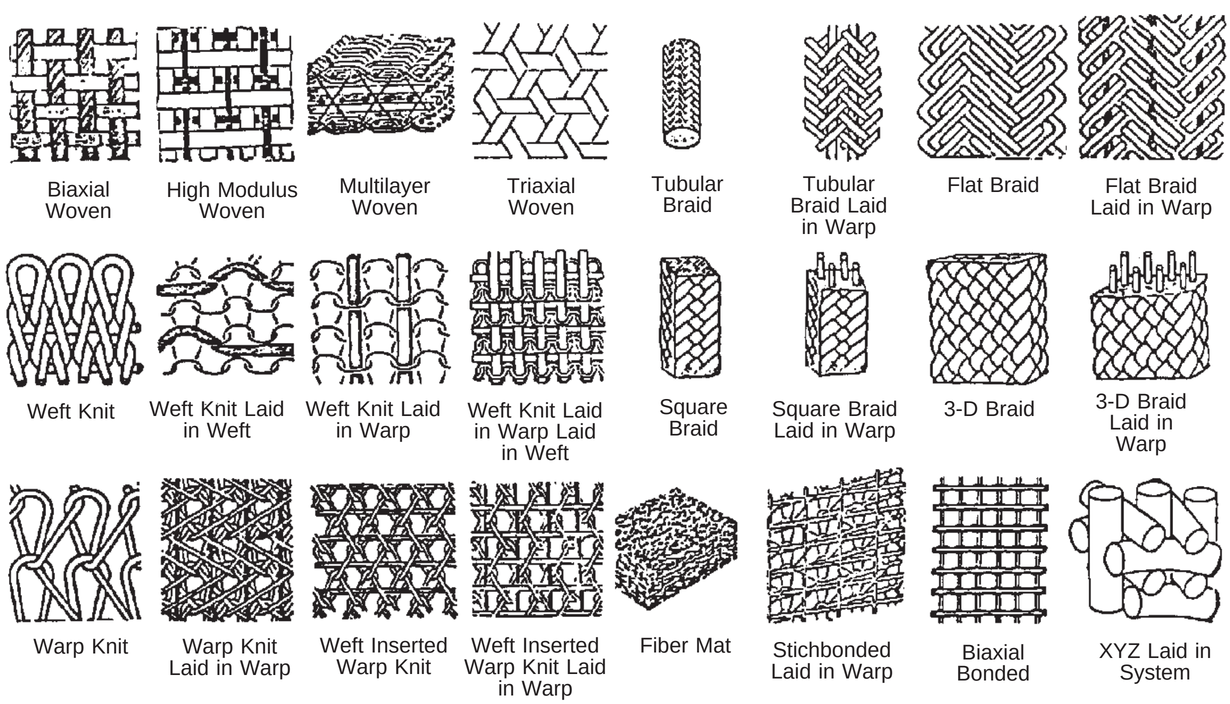


Figure 2-3 Various Forms of Reinforcement Architectures [Frank Ko, Drexel University]

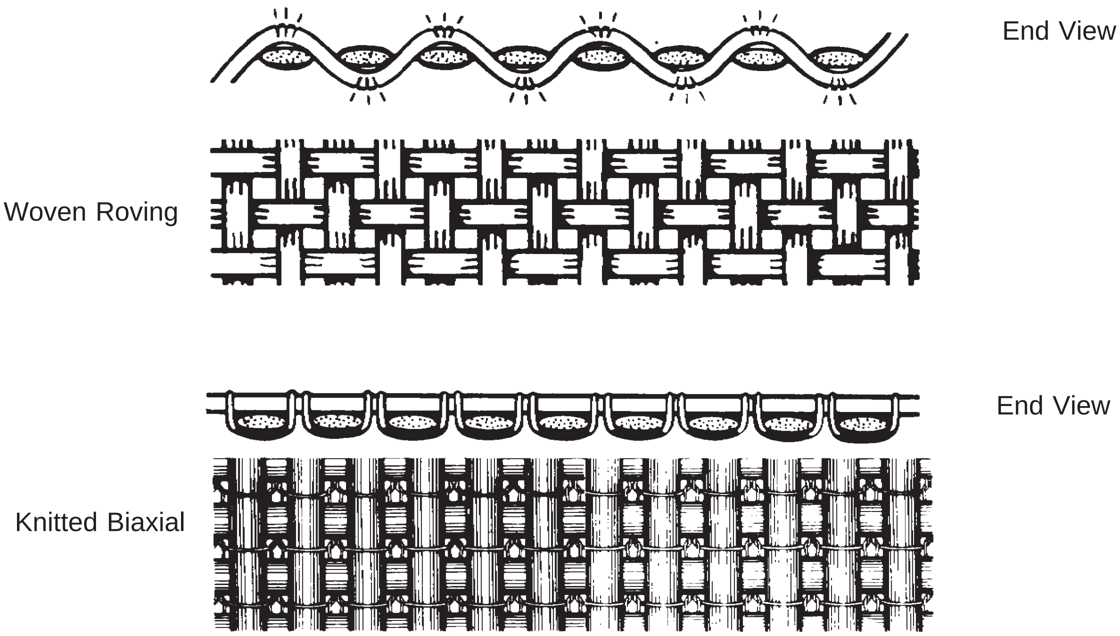


Figure 2-4 Comparison of Conventional Woven Roving and a Knitted Biaxial Fabric Showing Theoretical Kink Stress in Woven Roving [Composites Reinforcements, Inc.]

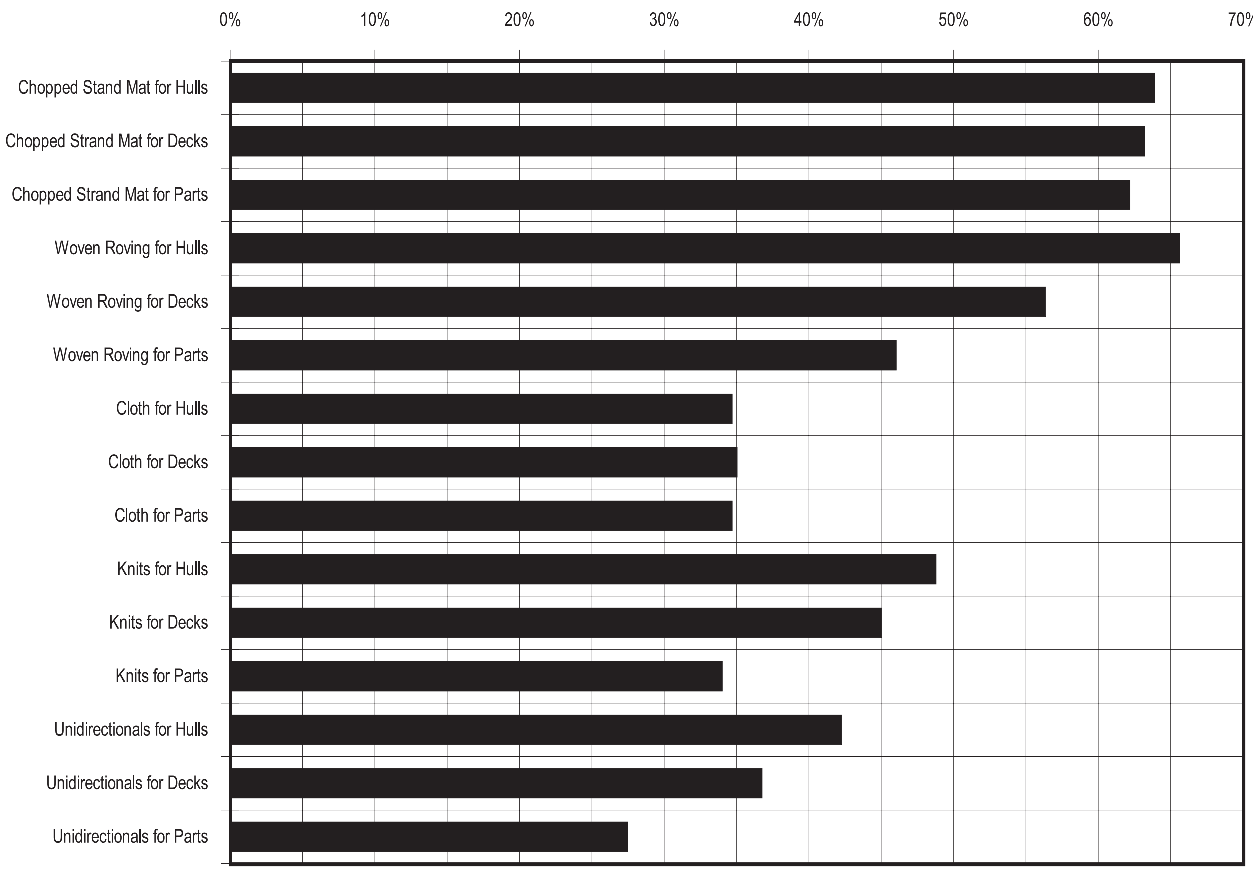


Figure 2-5 Marine Industry Reinforcement Style Use [EGA Survey]

Wovens

Woven composite reinforcements generally fall into the category of cloth or woven roving. The cloths are lighter in weight, typically from 6 to 10 ounces per square yard and require about 40 to 50 plies to achieve a one inch thickness. Their use in marine construction is limited to small parts and repairs. Particular weave patterns include plain weave, which is the most highly interlaced; basket weave, which has warp and fill yarns that are paired up; and satin weaves, which exhibit a minimum of interlacing. The satin weaves are produced in standard four-, five- or eight-harness configurations, which exhibit a corresponding increase in resistance to shear distortion (easily draped). Figure 2-2 shows some commercially available weave patterns.

Woven roving reinforcements consist of flattened bundles of continuous strands in a plain weave pattern with slightly more material in the warp direction. This is the most common type of reinforcement used for large marine structures because it is available in fairly heavy weights (24 ounces per square yard is the most common), which enables a rapid build up of thickness. Also, directional strength characteristics are possible with a material that is still fairly drapable. Impact resistance is enhanced because the fibers are continuously woven.

Knits

Knitted reinforcement fabrics were first introduced by Knytex® in 1975 to provide greater strength and stiffness per unit thickness as compared to woven rovings. A knitted reinforcement is constructed using a combination of unidirectional reinforcements that are stitched together with a nonstructural synthetic such as polyester. A layer of mat may also be incorporated into the construction. The process provides the advantage of having the reinforcing fiber lying flat versus the crimped orientation of woven roving fiber. Additionally, reinforcements can be oriented along any combination of axes. Superior glass to resin ratios are also achieved, which makes overall laminate costs competitive with traditional materials. Figure 2-4 shows a comparison of woven roving and knitted construction.

Omnidirectional

Omnidirectional reinforcements can be applied during hand lay-up as prefabricated mat or via the spray-up process as chopped strand mat. Chopped strand mat consists of randomly oriented glass fiber strands that are held together with a soluble resinous binder. Continuous strand mat is similar to chopped strand mat, except that the fiber is continuous and laid down in a swirl pattern. Both hand lay-up and spray-up methods produce plies with equal properties along the x and y axes and good interlaminar shear strength. This is a very economical way to build up thickness, especially with complex molds. Mechanical properties are less than other reinforcements.

Unidirectional

Pure unidirectional construction implies no structural reinforcement in the fill direction. Ultra high strength/modulus material, such as carbon fiber, is sometimes used in this form due to its high cost and specificity of application. Material widths are generally limited due to the difficulty of handling and wet-out. Anchor Reinforcements has recently introduced a line of unidirectionals that are held together with a thermoplastic web binder that is compatible with thermoset resin systems. The company claims that the material is easier to handle and cut than traditional pure unidirectional material. Typical applications for unidirectionals include stem and centerline stiffening as well as the tops of stiffeners. Entire hulls are fabricated from unidirectional reinforcements when an ultra high performance laminate is desired.

Resins

Polyester

The percent of manufacturers using various resin systems is represented in Figure 2-6. Polyester resins are the simplest, most economical resin systems that are easiest to use and show good chemical resistance. Almost one half million tons of this material is used annually in the United States. Unsaturated polyesters consist of unsaturated material, such as maleic anhydride or fumaric acid, that is dissolved in a reactive monomer, such as styrene. Polyester resins have long been considered the least toxic thermoset to personnel, although recent scrutiny of styrene emissions in the workplace has led to the development of alternate formulations (see Chapter Five). Most polyesters are air inhibited and will not cure when exposed to air. Typically, paraffin is added to the resin formulation, which has the effect of sealing the surface during the cure process. However, the wax film on the surface presents a problem for secondary bonding or finishing and must be physically removed. Non-air inhibited resins do not present this problem and are therefore, more widely accepted in the marine industry.

The two basic polyester resins used in the marine industry are orthophthalic and isophthalic. The ortho resins were the original group of polyesters developed and are still in widespread use. They have somewhat limited thermal stability, chemical resistance, and processability characteristics. The iso resins generally have better mechanical properties and show better chemical resistance. Their increased resistance to water permeation has prompted many builders to use this resin as a gel coat or barrier coat in marine laminates.

The rigidity of polyester resins can be lessened by increasing the ratio of saturated to unsaturated acids. Flexible resins may be advantageous for increased impact resistance, however, this comes at the expense of overall hull girder stiffness. Nonstructural laminate plies, such as gel coats and barrier veils, are sometimes formulated with more flexible resins to resist local cracking. On the other end of the spectrum are the low-profile resins that are designed to minimize reinforcement print-through. Typically, ultimate elongation values are reduced for these types of resins, which are represented by DCPD in Table 2-7.

Curing of polyester without the addition of heat is accomplished by adding accelerator along with the catalyst. Gel times can be carefully controlled by modifying formulations to match ambient temperature conditions and laminate thickness. The following combinations of curing additives are most common for use with polyesters:

Table 2-6 Polyester Resin Catalyst and Accelerator Combinations [Scott, *Fiberglass Boat Construction*]

Catalyst	Accelerator
Methyl Ethyl Keytone Peroxide (MEKP)	Cobalt Napthanate
Cuemene Hydroperoxide	Manganese Napthanate

Other resin additives can modify the viscosity of the resin if vertical or overhead surfaces are being laminated. This effect is achieved through the addition of silicon dioxide, in which case the resin is called thixotropic. Various other fillers are used to reduce resin shrinkage upon cure, a useful feature for gel coats.

Vinyl Ester

Vinyl ester resins are unsaturated resins prepared by the reaction of a monofunctional unsaturated acid, such as methacrylic or acrylic, with a bisphenol diepoxide. The resulting polymer is mixed with an unsaturated monomer, such as styrene. The handling and performance characteristics of vinyl esters are similar to polyesters. Some advantages of the vinyl esters, which may justify their higher cost, include superior corrosion resistance, hydrolytic stability, and excellent physical properties, such as impact and fatigue resistance. It has been shown that a 20 to 60 mil layer with a vinyl ester resin matrix can provide an excellent permeation barrier to resist blistering in marine laminates.

Epoxy

Epoxy resins are a broad family of materials that contain a reactive functional group in their molecular structure. Epoxy resins show the best performance characteristics of all the resins used in the marine industry. Aerospace applications use epoxy almost exclusively, except when high temperature performance is critical. The high cost of epoxies and handling difficulties have limited their use for large marine structures. Table 2-7 shows some comparative data for various thermoset resin systems.

Table 2-7 Comparative Data for Some Thermoset Resin Systems (castings)

Resin	Barcol Hardness	Tensile Strength psi x 10^3	Tensile Modulus psi x 10^5	Ultimate Elongation	1990 Bulk Cost $/lb
Orthophthalic Atlas P 2020	42	7.0	5.9	.91%	.66
Dicyclopentadiene (DCPD) Atlas 80-6044	54	11.2	9.1	.86%	.67
Isophthalic CoRezyn 9595	46	10.3	5.65	2.0%	.85
Vinyl Ester Derakane 411-45	35	11-12	4.9	5-6%	1.44
Epoxy Gouegon Pro Set 125/226	86D*	7.96	5.3	7.7%	4.39
*Hardness values for epoxies are traditionally given on the “Shore D” scale					+

Thermoplastics

Thermoplastics have one- or two-dimensional molecular structures, as opposed to three-dimensional structures for thermosets. The thermoplastics generally come in the form of molding compounds that soften at high temperatures. Polyethylene, polystyrene, polypropylene, polyamides and nylon are examples of thermoplastics. Their use in the marine industry has generally been limited to small boats and recreational items. Reinforced thermoplastic materials have recently been investigated for the large scale production of structural components. Some attractive features include no exotherm upon cure, which has plagued filament winding of extremely thick sections with thermosets, and enhanced damage tolerance. Processability and strengths compatible with reinforcement material are key areas currently under development.

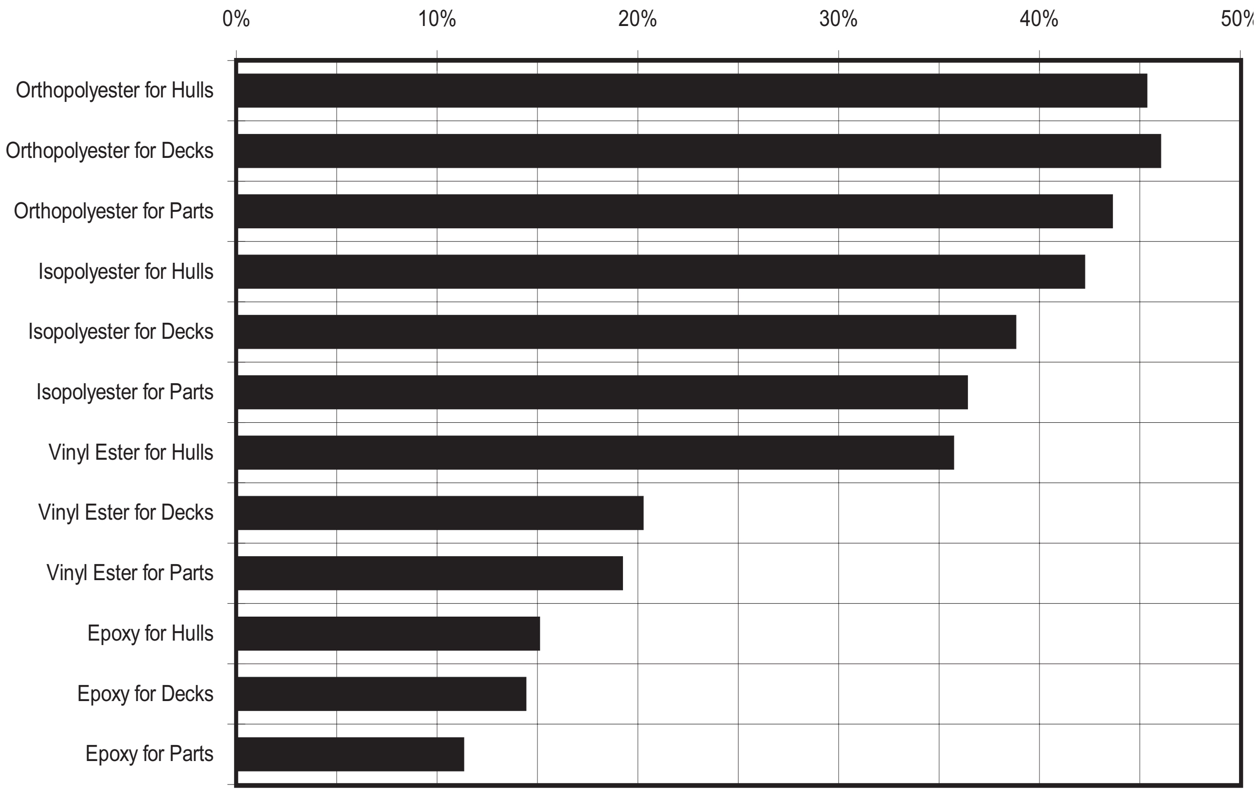


Figure 2-6 Marine Industry Resin System Use [EGA Survey]

Core Materials

Balsa

End grain balsa's closed-cell structure consists of elongated, prismatic cells with a length (grain direction) that is approximately sixteen times the diameter (see Figure 2-7). In densities between 6 and 16 pounds ft^3 (0.1 and 0.25 gms/cm^3), the material exhibits excellent stiffness and bond strength. Stiffness and strength characteristics are much like aerospace honeycomb cores Although the static strength of balsa panels will generally be higher than the PVC foams, impact energy absorption is lower. Local impact resistance is very good because stress is efficiently transmitted between sandwich skins. End-grain balsa is available in sheet form for flat panel construction or in a scrim-backed block arrangement that conforms to complex curves.

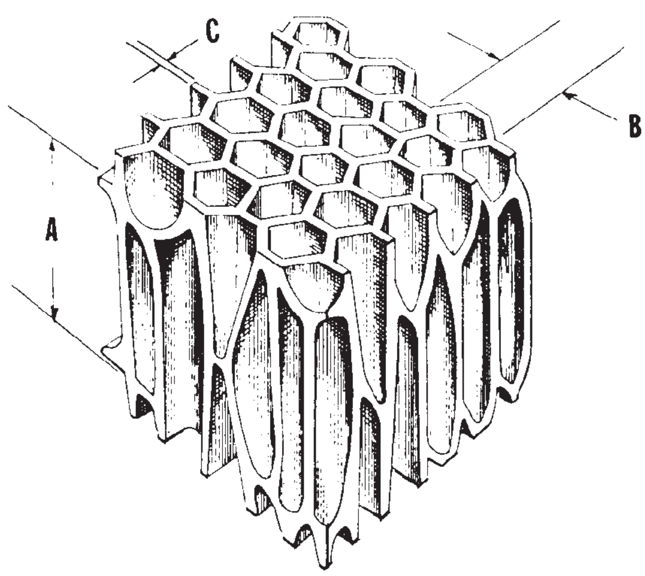


Figure 2-7 Balsa Cell Geometry with **A** = Average Cell Length = .025"; **B** = Average Cell Diameter = .00126"; **C** = Average Cell Wall Thickness = .00006" [Baltek Corporation]

Thermoset Foams

Foamed plastics such as cellular cellulose acetate (CCA), polystyrene, and polyurethane are very light (about 2 lbs/ft^3) and resist water, fungi and decay. These materials have very low mechanical properties and polystyrene will be attacked by polyester resin. These foams will not conform to complex curves. Use is generally limited to buoyancy rather than structural applications. Polyurethane is often foamed in-place when used as a buoyancy material.

Syntactic Foams

Syntactic foams are made by mixing hollow microspheres of glass, epoxy and phenolic into fluid resin with additives and curing agents to form a moldable, curable, lightweight fluid mass. Omega Chemical has introduced a sprayable syntactic core material called SprayCore™. The company claims that thicknesses of ⅜" can be achieved at densities between 30 and 43 lbs/ft^3. The system is being marketed as a replacement for core fabrics with superior physical properties. Material cost for a square foot of ⅜" material is approximately $2.20.

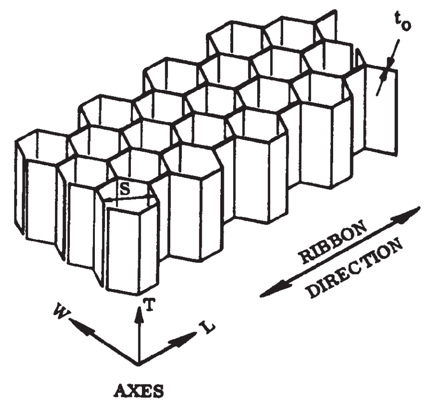


Figure 2-8 Hexagonal Honeycomb Geometry [MIL-STD-401B]

Cross Linked PVC Foams

Polyvinyl foam cores are manufactured by combining a polyvinyl copolymer with stabilizers, plasticizers, cross-linking compounds and blowing agents. The mixture is heated under pressure to initiate the cross-linking reaction and then submerged in hot water tanks to expand to the desired density. Cell diameters range from .0100 to .100 inches (as compared to .0013 inches for balsa). [2-2] The resulting material is thermoplastic, enabling the material to conform to compound curves of a hull. PVC foams have almost exclusively replaced urethane foams as a structural core material, except in configurations where the foam is "blown" in place. A number of manufacturers market cross-linked PVC products to the marine industry in sheet form with densities ranging from 2 to 12 pounds per ft^3. As with the balsa products, solid sheets or scrim backed block construction configurations are available.

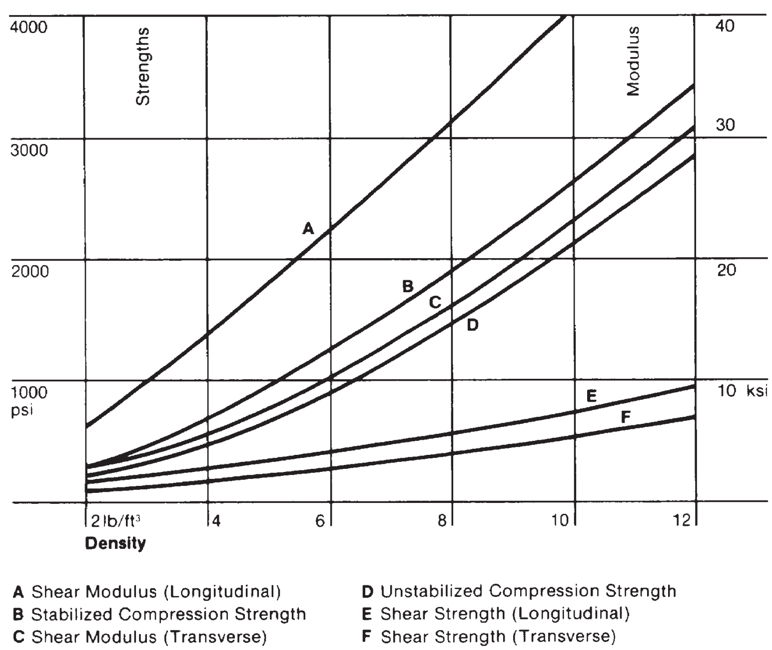


Figure 2-9 Core Strengths and Moduli for Various Core Densities of Aramid Honeycomb [Ciba-Geigy]

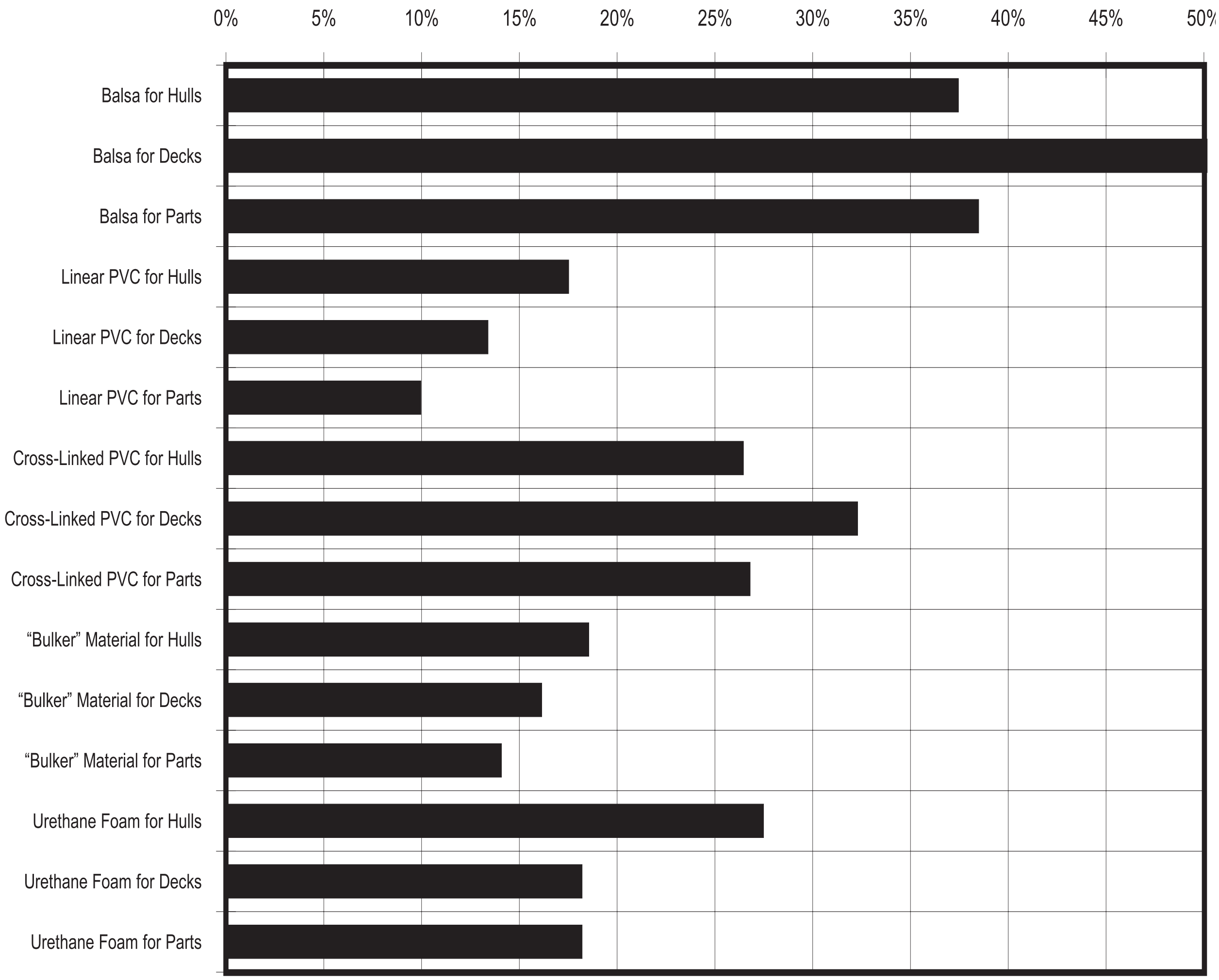


Figure 2-10 Marine Industry Core Material Use [EGA Survey]

Linear PVC Foam

Airex® and Core-Cell® are examples of linear PVC foam core produced for the marine industry. Unique mechanical properties are a result of a non-connected molecular structure, which allows significant displacements before failure. In comparison to the cross linked (non-linear) PVCs, static properties will be less favorable and impact will be better. For Airex,® individual cell diameters range from .020 to .080 inches. [2-3] Table 2-8 shows some of the physical properties of the core materials presented here.

Honeycomb

Various types of manufactured honeycomb cores are used extensively in the aerospace industry. Constituent materials include aluminum, phenolic resin impregnated fiberglass, polypropylene and aramid fiber phenolic treated paper. Densities range from 1 to 6 lbs/ft^3 and cell sizes vary from ⅛ to ⅜ inches. [2-4] Physical properties vary in a near linear fashion with density, as illustrated in Figure 2-9. Although the fabrication of extremely lightweight panels is possible with honeycomb cores, applications in a marine environment are limited due to the difficulty of bonding to complex face geometries and the potential for significant water absorption. The Navy has had some corrosion problems when an aluminum honeycomb core was used for ASROC housings. Data on a Nomex® phenolic resin honeycomb product is presented in Table 2-8.

PMI Foam

Rohm Tech, Inc. markets a polymrthacrylimide (PMI) foam for composite construction called Rohacell®. The material requires minimum laminating pressures to develop good peel strength. The most attractive feature of this material is its ability to withstand curing temperatures in excess of 350°F, which makes it attractive for use with prepreg reinforcements. Table 2-8 summarizes the physical properties of a common grade of Rohacell®.

Table 2-8 Comparative Data for Some Sandwich Core Materials

Core Material		Density		Tensile Strength		Compressive Strength		Shear Strength		Shear Modulus	
		lbs/ft^3	g/cm^3	psi	Mpa	psi	Mpa	psi	Mpa	psi x 10^3	Mpa
End Grain Balsa		7	112	1320	9.12	1190	8.19	314	2.17	17.4	120
		9	145	1790	12.3	1720	11.9	418	2.81	21.8	151
Cross-Linked PVC Foam	Termanto, C70.75	4.7	75	320	2.21	204	1.41	161	1.11	1.61	11
	Klegecell II	4.7	75	175	1.21	160	1.10			1.64	11
	Divinycell H-80	5.0	80	260	1.79	170	1.17	145	1.00	4.35	30
	Termanto C70.90	5.7	91	320	2.21	258	1.78	168	1.16	2.01	13
	Divinycell H-100	6.0	96	360	2.48	260	1.79	217	1.50	6.52	45
Linear Structural Foam	Core-Cell	3-4	55	118	0.81	58	0.40	81	0.56	1.81	12
		5-5.5	80	201	1.39	115	0.79	142	0.98	2.83	20
		8-9	210	329	2.27	210	1.45	253	1.75	5.10	35
Airex Linear PVC Foam		5-6	80-96	200	1.38	125	0.86	170	1.17	2.9	29
PMI Foam	Rohacell 71	4.7	75	398	2.74	213	1.47	185	1.28	4.3	30
	Rohacell 100	6.9	111	493	3.40	427	2.94	341	2.35	7.1	49
Phenolic Resin Honeycomb		6	96	n/a	n/a	1125	7.76	200	1.38	6.0	41
Polypropylene Honeycomb		4.8	77	n/a	n/a	218	1.50	160	1.10	n/a	n/a

FRP Planking

Seemann Fiberglass, Inc. developed a product called C-Flex® in 1973 to help amateurs build a cost effective one-off hull. The planking consists of rigid fiberglass rods held together with unsaturated strands of continuous fiberglass rovings and a light fiberglass cloth. The self-supporting material will conform to compound curves. Typical application involves a set of male frames as a form. The planking has more rigidity than PVC foam sheets, which eliminates the need for extensive longitudinal stringers on the male mold. A ⅛ inch variety of C-Flex® weighs about ½ pound dry and costs about $2.00 per square foot.

Core Fabrics

Various natural and synthetic materials are used to manufacture products to build up laminate thickness economically. One such product that is popular in the marine industry is Firet Coremat, a spun-bound polyester produced by Lantor. Hoechst Celanese has recently introduced a product called Trevira®, which is a continuous filament polyester. The continuous fibers seem to produce a fabric with superior mechanical properties. Ozite produces a core fabric called Compozitex™ from inorganic vitreous fibers. The manufacturer claims that a unique manufacturing process creates a mechanical fiber lock within the fabric. Although many manufacturers have had much success with such materials in the center of the laminate, the use of a Nonstructural thick ply near the laminate surface to eliminate print-through requires engineering forethought. The high modulus, low strength ply can produce premature cosmetic failures. Other manufacturers have started to produce "bulking" products that are primarily used to build up laminate thickness. Physical properties of core fabric materials are presented in Table 2-9.

Table 2-9 Comparative Data for Some "Bulking" Materials (impregnated with polyester resin to manufacturers' recommendation)

Material	Type	Dry Thickness inches	Cured Density lb/ft^2	Tensile Strength psi	Compressive Strength psi	Shear Strength psi	Flexural Modulus psi x 10^3	Cost $/ft^2
Coremat®	4mm	.157	37-41	551	3191	580	130	.44
Trevira®	Core 100	.100	75	2700	17700	1800	443	.28
Baltek®Mat	T-2000	.098	40-50	1364	—	1364	—	.31
Tigercore®	TY-3	.142	35	710	3000	1200	110	.44
Compozitex™	3mm	.118			Not tested			.35

Plywood

Plywood should also be mentioned as a structural core material, although fiberglass is generally viewed as merely a sheathing when used in conjunction with plywood. Exceptions to this characterization include local reinforcements in way of hardware installations where plywood replaces a lighter density core to improve compression properties of the laminate. Plywood is also sometimes used as a form for longitudinals, especially in way of engine mounts. Concern over the continued propensity for wood to absorb moisture in a maritime environment, which can cause swelling and subsequent delamination, has precipitated a decline in the use of wood in conjunction with FRP. Better process control in the manufacture of newer marine grade plywood should diminish this problem. The uneven surface of plywood can make it a poor bonding surface. Also, the low strength and low strain characteristics of plywood can lead to premature failures when used as a core with thin skins.

The technique of laminating numerous thin plies of wood developed by the Gougeon Brothers and known as wood epoxy saturation technique (WEST® System) eliminates many of the shortcomings involved with using wood in composite structures.

Composite Material Concepts

The marine industry has been saturated with the concept that we can build stronger and lighter vehicles through the use of composite materials. This may be true, but only if the designer fully understands how these materials behave. Without this understanding, material systems cannot be optimized and indeed can lead to premature failures. Wood construction requires an understanding of timber properties and joining techniques. Metal construction also involves an understanding of material specific properties and a knowledge of weld geometry and techniques. Composite construction introduces a myriad of new material choices and process variables. This gives the designer more design latitude and avenues for optimization. With this opportunity comes the greater potential for improper design.

Early fiberglass boats featured single-skin construction with laminates that contained a high percentage of resin. Because these laminates were not as strong as those built today and because builders' experience base was limited, laminates tended to be very thick, made from numerous plies of fiberglass reinforcement. These structures were nearly isotropic (properties similar in all directions parallel to the skin) and were very forgiving. In most cases, boats were overbuilt from a strength perspective to minimize deflections. With the emergence of sandwich laminates featuring thinner skins, the need to understand the structural response of laminates and failure mechanisms has increased.

Reinforcement and Matrix Behavior

The broadest definition of a composite material involves filamentary reinforcements supported in a matrix that starts as a liquid and ends up a solid via a chemical reaction. The reinforcement is designed to resist the primary loads that act on the laminate and the resin serves to transmit loads between the plies, primarily via shear. In compression loading scenarios, the resin can serve to "stabilize" the fibers for in-plane loads and transmit loads via direct compression for out-of-plane loads.

Mechanical properties for dry reinforcements and resin systems differ greatly. As an example, E-glass typically has a tensile strength of 500 x 10^3 psi (3.45 Gpa) and an ultimate elongation of 4.8%. An iso polyester resin typically has a tensile strength of 10 x 10^3 psi (69 Mpa) and an ultimate elongation of 2%. As laminates are stressed near their ultimate limits, resin systems generally fail first. The designer is thus required the ensure that a sufficient amount of reinforcement is in place to limit overall laminate stress. Contrast this to a steel structure, which may have a tensile yield strength of 70 x 10^3 psi (0.48 Gpa), an ultimate elongation of 20% and stiffnesses that are an order of magnitude greater than "conventional" composite laminates.

Critical to laminate performance is the bond between fibers and resin, as this is the primary shear stress transfer mechanism. Mechanical and chemical bonds transmit these loads. Resin formulation, reinforcement sizing, processing techniques and laminate void content influence the strength of this bond.

Directional Properties

With the exception of chopped strand mat, reinforcements used in marine composite construction utilize bundles of fibers oriented in distinct directions. Whether the reinforcements are aligned in a single direction or a combination thereof, the strength of the laminate will vary depending on the direction of the applied force. When forces do not align directly with reinforcement fibers, it is necessary for the resin system to transmit a portion of the load.

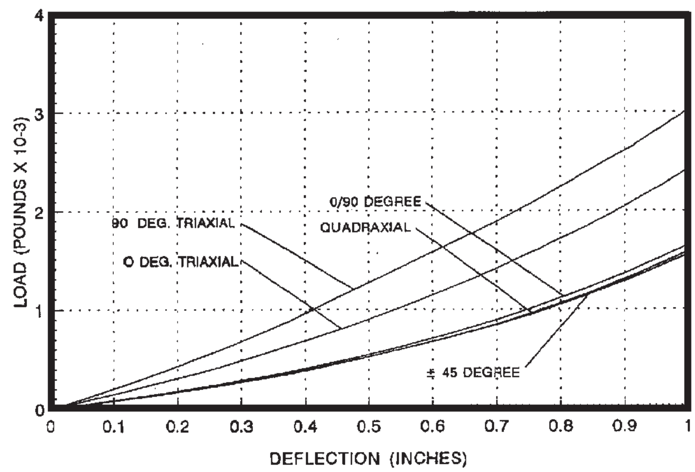


Figure 2-11 Comparison of Various Fiber Architectures Using the Hydromat Panel Tester on 3:1 Aspect Ratio Panels [Knytex]

"Balanced" laminates have a proportion of fibers in 0° and 90° directions. Some newer reinforcement products include ±45° fibers. Triaxial knits have ±45° fibers, plus either 0° or 90° fibers. Quadraxial knits have fibers in all four directions. Figure 2-11 illustrates the response of panels made with various knit fabrics subjected to out-of-plane loading.

Design and Performance Comparison with Metallic Structures

A marine designer with experience using steel or aluminum for hull structure will immediately notice that most composite materials have lower strength and stiffness values than the metal alloys used in shipbuilding. Values for strength are typically reported as a function of cross sectional area (ksi or Gpa). Because composite materials are much lighter than metals, thicker plating can be used. Figure 2-12 illustrates a comparison of specific strengths and stiffnesses (normalized for density) for selected structural materials. Because thicker panels are used for composite construction, panel stiffness can match or exceed that of metal hulls. Indeed, frame spacing for composite vessels is often much greater. For a given strength, composite panels may be quite a bit more flexible, which can lead to in-service deflections that are larger than for metal hulls. Figure 2-13 shows the effect of utilizing sandwich construction.

The above discussion pertains to panel behavior when resisting hydrostatic and wave slamming loads. If the structure of a large ship in examined, then consideration must be given to the overall hull girder bending stiffness. Because structural material cannot be located farther from the neutral axis (as is the case with thicker panels), the overall stiffness of large ships is limited when quasi-isotropic laminates are used. This has led to concern about main propulsion machinery alignment when considering construction of FRP ships over 300 feet (91 meters) in length. With smaller, high performance vessels, such as racing sailboats, longitudinal stiffness is obtained through the use of longitudinal stringers, 0° unidirectional reinforcements, or high modulus materials, such as carbon fiber.

Damage and failure modes for composites also differ from metals. Whereas a metal grillage will transition from elastic to plastic behavior and collapse in its entirety, composite panels will fail one ply at a time, causing a change in strength and stiffness, leading ultimately to catastrophic failure. This would be preceded by warning cracks at ply failure points. Crack propagation associated with metals typically does not occur with composites. Interlaminar failure between successive plies is much more common. This scenario has a much better chance of preserving watertight integrity.

Because composite laminates do not exhibit the classic elastic to plastic stress-strain behavior that metals do, safety factors based on ultimate strength are generally higher, especially for compressive failure modes. Properly designed composite structures see very low stress levels in service, which in turn should provide a good safety margin for extreme loading cases.

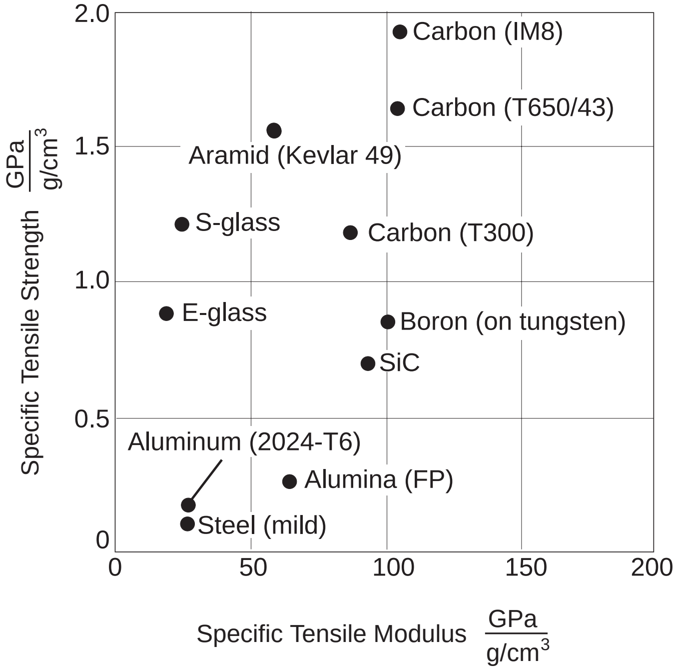
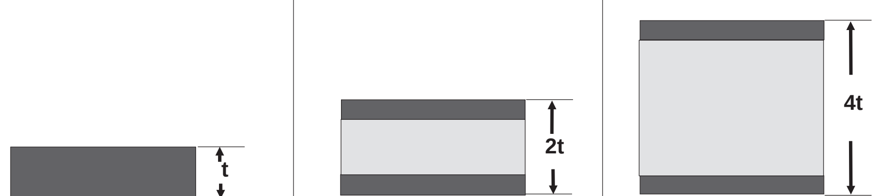


Figure 2-12 Specific Strength and Stiffness of Various Construction Materials [DuPont]

Many design and performance factors make direct comparison between composites and metals difficult. However, it is instructive to compare some physical properties of common shipbuilding materials. Table 2-10 provides a summary of some constituent material characteristics.



Relative Stiffness	100	700	3700
Relative Strength	100	350	925
Relative Weight	100	103	106

Figure 2-13 Strength and Stiffness for Cored and Solid Construction [Hexcel, The Basics on Sandwich Construction]

Table 2-10 Overview of Shipbuilding Construction Materials

Material		Density		Tensile Strength		Tensile Modulus		Ultimate Elongation	1995 Cost
		lbs/ft^3	gm/cm^3	psi x 10^3	Mpa	psi x 10^6	Gpa	%	$/lb
Resins	Orthophthalic Polyester	76.7	1.23	7	48.3	.59	4.07	1	1.05
	Isophthalic Polyester	75.5	1.21	10.3	71.1	.57	3.90	2	1.19
	Vinyl Ester	69.9	1.12	11-12	76-83	.49	3.38	4-5	1.74
	Epoxy (Gougeon Proset)	74.9	1.20	7-11	48-76	.53	3.66	5-6	3.90
	Phenolic	71.8	1.15	5.1	35.2	.53	3.66	2	1.10
Fibers	E-Glass (24 oz WR)	162.4	2.60	500	3450	10.5	72.45	4.8	1.14
	S- Glass	155.5	2.49	665	4589	12.6	86.94	5.7	5.00
	Kevlar® 49	90	1.44	525	3623	18	124.2	2.9	20.00
	Carbon-PAN	109.7	1.76	350-700	2415-4830	33-57	227-393	0.38-2.0	12.00
Cores	End Grain Balsa	7	0.11	1.320	9.11	.370	2.55	n/a	3.70
	Linear PVC (Airex R62.80)	5-6	.08-0.1	0.200	1.38	0.0092	0.06	30	5.20
	Cross-Linked PVC (Diab H-100)	6	0.10	0.450	3.11	0.0174	0.12	n/a	5.95
	Honeycomb (Nomex® HRH-78)	6	0.10	n/a	n/a	0.0600	0.41	n/a	13.25
	Honeycomb (Nidaplast H8PP)	4.8	0.08	n/a	n/a	n/a	n/a	n/a	.80
Laminates	Solid Glass/Polyester *hand lay-up*	96	1.54	20	138	1.4	9.66	n/a	2.50
	Glass/Polyester Balsa Sandwich *vacuum assist*	24	0.38	6	41	0.4	2.76	n/a	4.00
	Glass/Vinyl Ester PVC Sandwich *SCRIMP®*	18	0.29	6	41	0.4	2.76	n/a	5.00
	Solid Carbon/Epoxy *filament wound*	97	1.55	88	607	8.7	60	n/a	10.00
	Carbon/Epoxy Nomex Sandwich *prepreg*	9	0.14	9	62	0.5	3.45	n/a	20.00
Metals	ABS Grd A (ASTM 131)	490.7	7.86	58	400	29.6	204	21	0.29
	ABS Grd AH (ASTM A242)	490.7	7.86	71	490	29.6	204	19	0.34
	Aluminum (6061-T6)	169.3	2.71	45	310	10.0	69	10	2.86
	Aluminum (5086-H34)	165.9	2.66	44	304	10.0	69	9	1.65
Wood	Douglas Fir	24.4	0.39	13.1	90	1.95	13.46	n/a	1.97
	White Oak	39.3	0.63	14.7	101	1.78	12.28	n/a	1.07
	Western Red Cedar	21.2	0.34	7.5	52	1.11	7.66	n/a	2.26
	Sitka Spruce	21.2	0.34	13.0	90	1.57	10.83	n/a	4.48

Note: The values used in this table are for illustration only and should not be used for design purposes. In general, strength is defined as yield strength and modulus will refer to the material's initial modulus. A core thickness of 1" with appropriate skins was assumed for the sandwich laminates listed.

Material Properties and Design Allowables

Although it is often difficult to predict the loads that will act on a structure in the marine environment, it is equally difficult to establish material property data and design allowables that will lead to a well engineered structure. It is first important to note that "attractive" property data for a reinforcement as presented in Figure 2-12, may apply only to fibers. Designers always need to use data on laminates, which include fibers and resin manufactured in a fashion similar to the final product.

The aerospace design community typically has material property data for unidirectional reinforcements according to the notation in Figure 2-14, while the marine industry uses the notation of Figure 2-15. Because of extreme safety and weight considerations, the aerospace industry has made considerable investment to characterize relevant composite materials for analytical evaluation. Unfortunately, these materials are typically carbon/epoxy prepregs, which are seldom used in marine construction. The best that a marine designer can expect is primary plane (1-2) data. Most available test data is in the primary or "1" axis direction. The type of data that exists, in decreasing order of availability/reliability is: Tensile, Flexural, Compressive, Shear, Poisson's Ratio.

Test data is difficult to get for compression and shear properties because of problems with test fixtures and laminate geometries. Data that is generated usually shows quite a bit of scatter. This must be kept in mind when applying safety factors or when developing design allowable physical property data.

It should be noted that stiffness data or modulus of elasticity values are more repeatable than strength values. As many composite material design problems are governed by deflection rather than stress limits, strength criteria and published material properties should be used with caution.

The type of loading and anticipated type of failure generally determines which safety factors are applied to data derived from laboratory testing of prototype laminates. If the loading and part geometry are such that long term static or fatigue loads can produce a dynamic failure in the structure, a safety factor of 4.0 is generally applied. If loading is transient, such as with slamming, or the geometry is such that gradual failure would occur, then a safety factor of 2.0 is applied. With once-in-a-lifetime occurrences, such as underwater explosions for military vessels, a safety factor of 1.5 is generally applied. Other laminate performance factors, such as moisture, fatigue, impact and the effect of holes influence decisions on design allowables.

Appendix A contains test data on a variety of common marine reinforcements tested with ASTM methods by Art Wolfe at Structural Composites, Inc.; Dave Jones at Sigma Labs; Tom Juska from the Navy's NSWC; and Rick Strand at Comtrex. In limited cases, data was supplied by material suppliers. Laminates were fabricated using a variety of resin systems and fabrication methods, although most were made using hand lay-up techniques. In general, test panels made on flat tables exhibit properties superior to as-built marine structures. Note that higher fiber content laminates will be thinner for the same amount of reinforcement used. This will result in higher mechanical values, which are reported as a function of cross sectional area. However, if the same amount of reinforcement is present in high- and low-fiber content laminates, they may both have the same "strength" in service. Indeed, the low-fiber content may have superior flexural strength as a result of increased thickness. Care must always be exercised in interpreting test data. Additionally, samples should be fabricated by the shop that will produce the final part and tested to verify minimum properties. As can be seen in Appendix A, complete data sets are not available for most materials. Where available, data is presented for properties measured in 0°, 90° and ±45° directions. Shear data is not presented due to the wide variety in test methods used. Values for Poission's ratio are seldom reported.

Cost and Fabrication

Material and production costs for composite marine construction are closely related. Typically, the higher cost materials will require higher-skilled labor and more sophisticated production facilities. The cost of materials will of course vary with market factors.

Material Costs

Table 2-10 provides an overview of material costs associated with marine composite construction. It is difficult to compare composite material cost with conventional homogeneous shipbuilding materials, such as wood or metals, on a pound-for-pound basis. Typically, an optimized structure made with composites will weigh less than a metallic structure, especially if sandwich techniques are used. Data in Table 2-10 is provided to show designers the relative costs for "common" versus "exotic" composite shipbuilding materials.

Production Costs

Production costs will vary greatly with the type of vessel constructed, production quantities and shipyard efficiency. Table 2-11 is compiled from several sources to provide designers with some data for performing preliminary labor cost estimates.

Table 2-11 Marine Composite Construction Productivity Rates

Source	Type of Construction	Application	Lbs/Hour*	Ft^2/Hour†	Hours/Ft^2‡
Scott *Fiberglass Boat Construction*	Single Skin with Frames	Recreational	20*	33†	.03‡
		Military	12*	20†	.05‡
	Sandwich Construction	Recreational	10*	17†	.06‡
		Military	6*	10†	.10‡
BLA *Combatant Feasibility Study*	Single Skin with Frames	Flat panel (Hull)	13**	22**	.05**
		Stiffeners & Frames	5**	9**	.12**
	Core Preparation for Sandwich Construction	Flat panel (Hull)	26**	43**	.02**
		Stiffeners	26**	43**	.02**
	Vacuum Assisted Resin Transfer Molding (VARTM)	Flat panel (Hull)	10§	43§	.02§
		Stiffeners	7§	14§	.07§

* Based on mat/woven roving laminate
** Based on one WR or UD layer
† Single ply of mat/woven roving laminate
‡ Time to laminate one ply of mat/woven roving (reciprocal of Ft^2/hr)
§ Finished single ply based on weight of moderately thick single-skin laminate

Design Optimization Through Material Selection

Composite materials afford the opportunity for optimization through combinations of reinforcements, resins, and cores. Engineering optimization always involves tradeoffs among performance variables. Table 2-12 is provided to give an overview of how constituent materials rank against their peers, on a qualitative basis. Combinations of reinforcement, resin and core systems may produce laminates that can either enhance or degrade constituent material properties.

Table 2-12 Qualitative Assessment of Constituent Material Properties

	Fiber			Resin					Core					
	E-Glass	Kevlar	Carbon	Polyester	Vinyl Ester	Epoxy	Phenolic	Thermoplastic	Balsa	Cross Link PVC	Linear PVC	Nomex/Alum Honeycomb	Thermoplastic Honeycomb	Syntactic Foam
Static Tensile Strength	■	■	■	□	□	■	□	□	■	■	■	□	□	□
Static Tensile Stiffness	□	■	■	□	□	□	□	□	■	□	□	■	□	□
Static Compressive Strength	■	□	□	□	□	□	□	□	■	□	■	■	□	□
Static Compressive Stiffness	□	□	■	□	□	□	□	□	■	□	□	■	□	□
Fatigue Performance	□	■	■	□	■	■	□	■	■	□	■	□	■	□
Impact Performance	■	■	□	□	■	■	□	■	□	■	■	□	□	□
Water Resistance	■	□	□	□	■	■	□	■	□	■	■	□	□	□
Fire Resistance	■	□	□	□	□	□	■	□	■	□	□	■	□	□
Workability	■	□	□	■	□	□	□	□	■	□	□	□	□	■
Cost	■	□	□	■	□	□	□	■	■	□	□	□	■	■

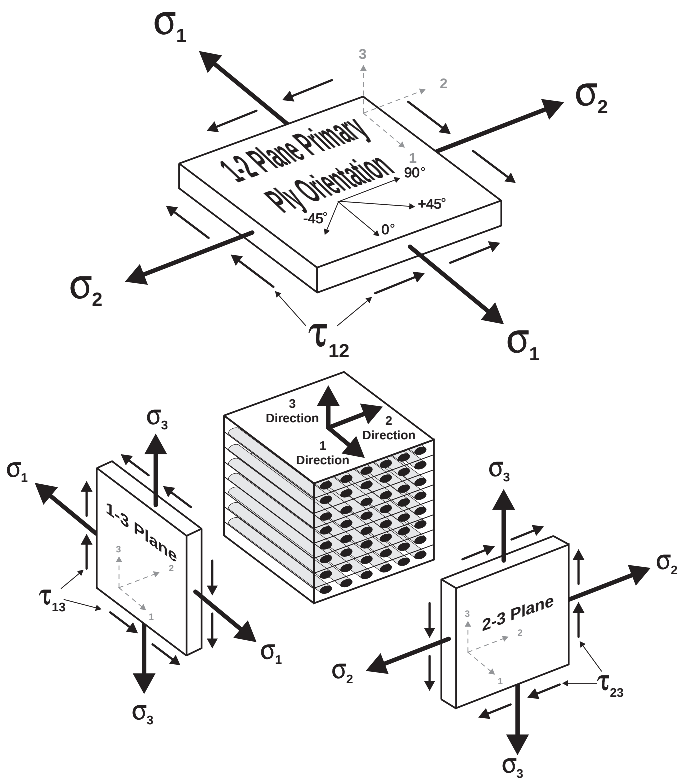
■ Good Performance
□ Fair Performance

Figure 2-14
Lamina

A lamina is a single ply (unidirectional) in a laminate, which is made up of a series of layers.

The illustration to the right depicts composite lamina notation used to describe applied stresses. The notation for primary ply axes is also presented.

The accompanying table denotes the strength and stiffness data used to characterize composite laminae based on this geometric description.



Stiffness	1	Longitudinal	Tensile Modulus	E_1^t	Compressive Modulus	E_1^c
	2	Transverse	Tensile Modulus	E_2^t	Compressive Modulus	E_2^c
	3	Thickness	Tensile Modulus	E_3^t	Compressive Modulus	E_3^c
	12	Longitudinal/ Transverse		Shear Modulus	G_{12}	
	13	Longitudinal/ Thickness		Shear Modulus	$G_{13} = G_{12}$	
	23	Transverse/ Thickness		Shear Modulus	$G_{23} = E_2 / [2(1+\nu_{23})]$	
Strength	1	Longitudinal	Tensile Strength	$\sigma_1^{t\ ult}$	Compressive Strength	$\sigma_1^{c\ ult}$
	2	Transverse	Tensile Strength	$\sigma_2^{t\ ult}$	Compressive Strength	$\sigma_2^{c\ ult}$
	3	Thickness	Tensile Strength	$\sigma_3^{t\ ult}$	Compressive Strength	$\sigma_3^{c\ ult}$
	12	Longitudinal/ Transverse		Shear Strength	τ_{12}^{ult}	
	13	Longitudinal/ Thickness		Shear Strength	$\tau_{13}^{ult} = \tau_{12}^{ult}$	
	23	Transverse/ Thickness		Shear Strength	τ_{23}^{ult}	

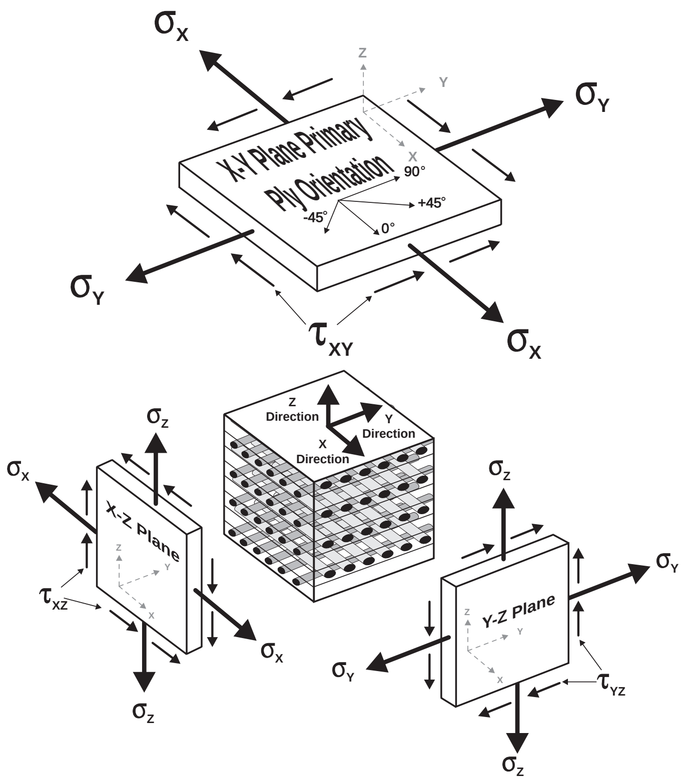
Poisson's Ratio				
Direction:	12 (Major)	21 (Minor)	31	23
Notation:	ν_{12}^t, ν_{12}^c	ν_{21}^t, ν_{21}^c	ν_{31}^t, ν_{31}^c	ν_{23}^t, ν_{23}^c

Figure 2-15
Laminate

A laminate consists of multiple layers of lamina with unique orientations.

The illustration to the right depicts composite laminate notation used to describe applied stresses. The notation for primary ply axes is also presented.

The accompanying table denotes the strength and stiffness data used to characterize composite laminates based on this geometric description.



Stiffness	X	Longitudinal	Tensile Modulus	E_x^t	Compressive Modulus	E_x^c
	Y	Transverse	Tensile Modulus	E_y^t	Compressive Modulus	E_y^c
	Z	Thickness	Tensile Modulus	E_z^t	Compressive Modulus	E_z^c
	XY	Longitudinal/ Transverse	Shear Modulus	G_{xy}		
	XZ	Longitudinal/ Thickness	Shear Modulus	G_{xz}		
	YZ	Transverse/ Thickness	Shear Modulus	G_{yz}		
Strength	X	Longitudinal	Tensile Strength	$\sigma_x^{t\ ult}$	Compressive Strength	$\sigma_x^{c\ ult}$
	Y	Transverse	Tensile Strength	$\sigma_y^{t\ ult}$	Compressive Strength	$\sigma_y^{c\ ult}$
	Z	Thickness	Tensile Strength	$\sigma_z^{t\ ult}$	Compressive Strength	$\sigma_z^{c\ ult}$
	XY	Longitudinal/ Transverse	Shear Strength	τ_{xy}^{ult}		
	XZ	Longitudinal/ Thickness	Shear Strength	τ_{xz}^{ult}		
	YZ	Transverse/ Thickness	Shear Strength	τ_{yz}^{ult}		

Poisson's Ratio

Direction:	XY (Major)	YX (Minor)	ZX	YZ
Notation:	ν_{xy}^t, ν_{xy}^c	ν_{yx}^t, ν_{yx}^c	ν_{zx}^t, ν_{zx}^c	ν_{yz}^t, ν_{yz}^c

Hull as a Longitudinal Girder

Classical approaches to ship structural design treat the hull structure as a beam for purposes of analytical evaluation. [3-1] The validity of this approach is related to the vessel's length to beam and length to depth ratios. Consequently, beam analysis is not the primary analytical approach for small craft. Hull girder methods are usually applied to vessels with length/depth (L/D) ratios of 12 or more, which usually corresponds to vessels greater than 100 feet (30 meters). Very slender hull forms, such as a canoe or catamaran hull, may have an L/D much greater than 12. Nevertheless, it is always instructive to regard hull structure as a beam when considering forces that act on the vessel's overall length. By determining which elements of the hull are primarily in tension, compression or shear, scantling determination can be approached in a more rational manner. This is particularly important when designing with anisotrophic materials, such as composites, where orientation affects the structure's load carrying capabilities to such a great extent.

A variety of different phenomena contribute to the overall longitudinal bending moments experienced by a ship's hull structure. Analyzing these global loading mechanisms statically is not very realistic with smaller craft. Here, dynamic interaction in a seaway will generally produce loadings in excess of what static theory predicts. However, empirical information has led to the development of accepted safety factors that can be applied to the statically derived stress predictions. Force producers are presented here in an order that corresponds to decreasing vessel size, i.e., ship theory first.

Still Water Bending Moment

Before a ship even goes to sea, some stress distribution profile exists within the structure. Figure 3-1 shows how the summation of buoyancy and weight distribution curves leads to the development of load, shear and moment diagrams. Stresses apparent in the still water condition generally become extreme only in cases where concentrated loads are applied to the structure, which can be the case when holds in a commercial vessel are selectively filled. The still water bending moment (SWBM) is an important concept for composites design because fiberglass can be susceptible to creep or fracture when subjected to long term loads. Static fatigue of glass fibers can reduce their load carrying capability by as much as 70 to 80% depending on load duration, temperature, moisture conditions and other factors. [3-2]

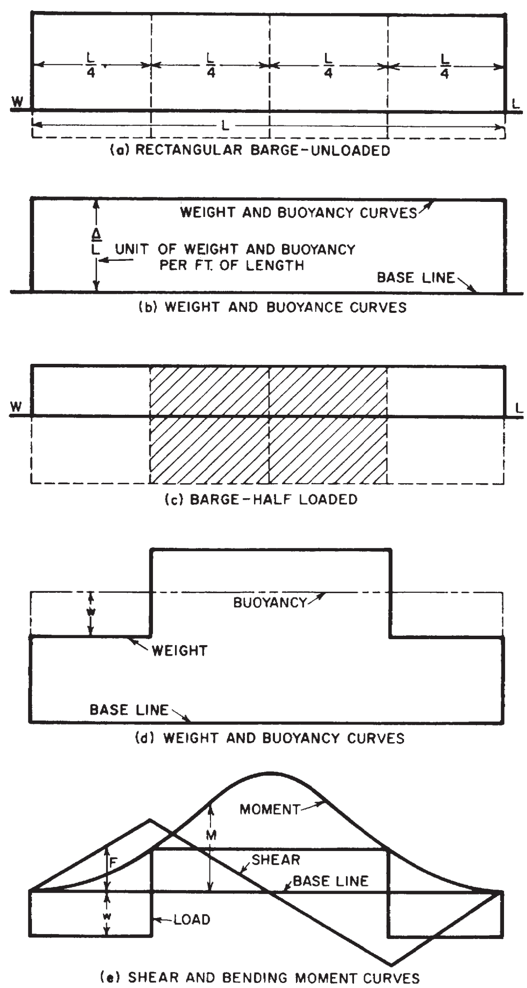


Figure 3-1 Bending Moment Development of Rectangular Barge in Still Water [*Principles of Naval Architecture*]

Wave Bending Moment

A static approach to predicting ship structure stresses in a seaway involves the superposition of a trochoidal wave with a wavelength equal to the vessel's length in a hogging and sagging condition, as shown in Figure 3-2. The trochoidal wave form was originally postulated by Froude as a realistic two-dimensional profile, which was easily defined mathematically. The height of the wave is usually taken as $L/9$ (L < 100 feet or 30 meters), $L/20$ (L > 100 feet or 30 meters) or $1.1L^{1/2}$ (L > 500 feet) or $0.6L^{.6}$ (L > 150 meters). Approximate calculation methods for maximum bending moments and shearing forces have been developed as preliminary design tools for ships over 300 feet (91 meters) long. [3-3] Except for very slender craft, this method will not apply to smaller vessels.

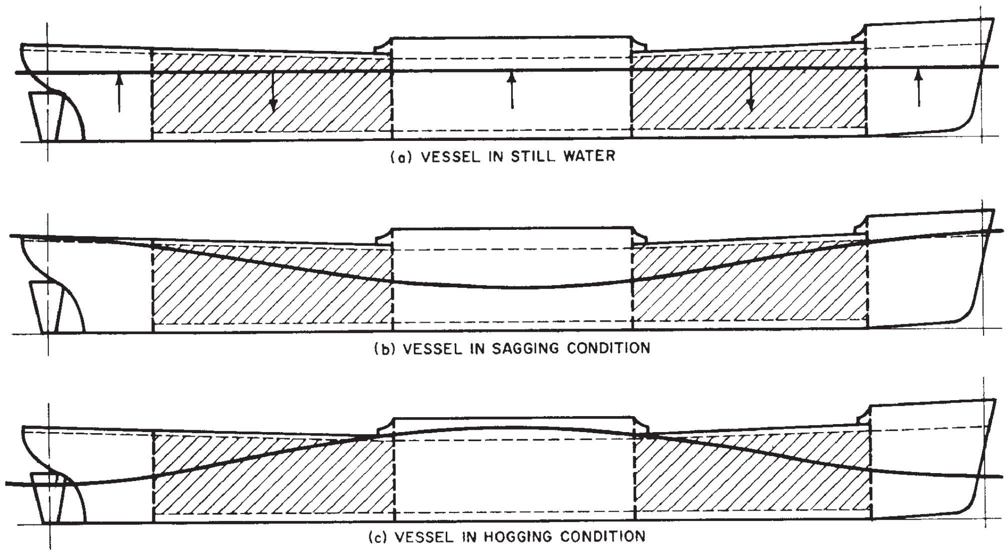


Figure 3-2 Superposition of Static Wave Profile [*Principles of Naval Architecture*]

Ship Oscillation Forces

The dynamic response of a vessel operating in a given sea spectrum is very difficult to predict analytically. Accelerations experienced throughout the vessel vary as a function of vertical, longitudinal and transverse location. These accelerations produce virtual increases of the weight of concentrated masses, hence additional stress. The designer should have a feel for the worst locations and dynamic behavior that can combine to produce extreme load scenarios. Figure 3-3 is presented to define the terms commonly used to describe ship motion. It is generally assumed that combined roll and pitch forces near the deck edge forward represents a "worst case" condition of extreme accelerations for the ship.

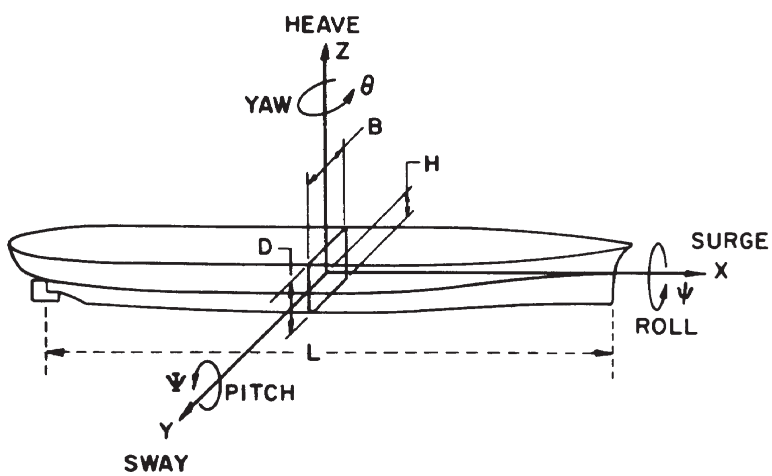


Figure 3-3 Principal Axes and Ship Motion Nomenclature [Evans, *Ship Structural Design Concepts*]

Dynamic Phenomena

Dynamic loading or vibration can be either steady state, as with propulsion system induced phenomena, or transient, such as with slamming through waves. In the former case, load amplitudes are generally within the design limits of hull structural material. However, the fatigue process can lead to premature failures, especially if structural components are in resonance with the forcing frequency. A preliminary vibration analysis of major structural elements (hull girder, engine foundations, deck houses, masts, etc.) is generally prudent to ensure that natural frequencies are not near shaft and blade rate for normal operating speeds. [3-4] Schlick [3-5] proposed the following empirical formula to predict the first-mode (2-node) vertical natural frequency for large ships:

$$N_{2v} = C_1 \sqrt{\frac{I}{\Delta L^3}} \tag{3-1}$$

where:

L = length between perpendiculars, feet
Δ = displacement, tons
I = midship moment of inertia, in^{2}ft^2
C_1 = constant according to ship type
= 100,000 for small coastal tankers, 300-350 feet
= 130,000 for large, fully loaded tankers
= 143,000 suggested by Noonan for large tankers
= 156,850 for destroyers

The transient dynamic loading referred to generally describes events that occur at much higher load amplitudes. Slamming in waves is of particular interest when considering the design of high-speed craft. Applying an acceleration factor to the static wave bending analysis outlined above can give some indication of the overall girder stresses produced as a high-speed craft slams into a wave. Other hull girder dynamic phenomena of note include springing and whipping of the hull when wave encounter frequency is coincident with hull natural frequency.

Sailing Vessel Rigging Loads

The major longitudinal load producing element associated with sailing vessels is the mast operating in conjunction with the headstay and backstay. The mast works in compression under the combined action of the aforementioned longitudinal stays and the more heavily loaded athwartship shroud system. Hull deflection is in the sagging mode, which can be additive with wave action response.

Transverse Bending Loads

Transverse loading on a ship's hull is normally of concern only when the hull form is very long and slender. Global forces are the result of beam seas. In the case of sailing vessels, transverse loads can be significant when the vessel is sailing upwind in a heeled condition. Methods for evaluating wave bending moment should be used with a neutral axis that is parallel to the water.

Torsional Loading

Torsional loading of hull structures is often overlooked because there is no convenient analytical approach that has been documented. Quartering seas can produce twisting moments within a hull structure, especially if the hull has considerable beam. In the case of multihulls, this loading phenomena often determines the configuration of cross members. Vessels with large deck openings are particularly susceptible to applied torsional loads. New reinforcement materials are oriented with fibers in the bias direction (±45°), which makes them extremely well suited for resisting torsional loading.

Slamming

The loads on ship structures are reasonably well established (e.g. ***Principles of Naval Architecture***, etc.), while the loads on small craft structures have received much less attention in the literature. There are some generalizations which can be made concerning these loads, however. The dominant loads on ships are global in-plane loads (loads affecting the entire structure and parallel to the hull plating), while the dominant loads on small craft are local out of plane loads (loads normal to the hull surface over local portions of the hull surface). As a result, structural analysis of ships is traditionally approached by approximating the entire ship as a box beam, while the structural analysis of small craft is approached using local panel analysis. The analysis of large boats (or small ships) must include both global and local loads, as either may be the dominant factor. Since out-of-plane loads are dominant for small craft, the discussion of these loads will center on small craft. However, much of the discussion could be applied to ships or other large marine structures. The American Bureau of Shipping provides empirical expressions for the derivation of design heads for sail and power vessels. [3-6, 3-7]

Out-of-plane loads can be divided into two categories: distributed loads (such as hydrostatic and hydrodynamic loads) and point loads (such as hauling or keel, rig, and rudder loads on sail boats, or strut, rudder or engine mounts for power boats). The hydrostatic loads on a boat at rest are relatively simple and can be determined from first principles. Hydrodynamic loads are very complex, however, and have not been studied extensively, thus they are usually treated in an extremely simplified manner. The most common approach is to increase the static pressure load by a fixed proportion, called the dynamic load factor. [3-8] The sources of point loads vary widely, but most can be estimated from first principles by making a few basic assumptions.

Hydrodynamic Loads

There are several approaches to estimating the hydrodynamic loads for planing power boats. However, most are based on the first comprehensive work in this area, performed by Heller and Jasper. The method is based on relating the strain in a structure from a static load to the strain in a structure from a dynamic load of the same magnitude. The ratio of the dynamic strain to the static strain is called the "response factor," and the maximum response factor is called the "dynamic load factor." This approach is summarized here with an example of this type of calculation. Heller and Jasper instrumented and obtained data on an aluminum hull torpedo boat (YP 110) and then used this data as a basis for the empirical aspects of their load calculation. An example of the pressure data is presented in Figure 3-4. The dynamic load factor is a function of the impact pressure rise time, t_o, over the natural period of the structure, T, and is presented in Figure 3-5, where c/c_c is the fraction of critical damping. The theoretical development of the load prediction leads to the following equations:

Maximum Impact Force Per Unit Length:

$$P_0 = \frac{3W}{2L} \times \left(1 + \frac{y_{CG}}{g}\right) \qquad (3\text{-}2)$$

where:

p_0 = maximum impact force per unit length

W = hull weight

L = waterline length

y_{CG} = vertical acceleration of the CG

g = gravitational acceleration

Maximum Effective Pressure at the Keel

$$P_{01} = \frac{3p_0}{G} \tag{3-3}$$

where:

p_{01} = maximum effective pressure at the keel

G = half girth

Maximum Effective Pressure

$$\overline{P} = p_{01} \times DLF \tag{3-4}$$

where:

$\overline{P}$ = the maximum effective pressure for design

DLF = the Dynamic Load Factor from Figure 3-5 (based on known or measured critical damping)

An example of the pressure calculation for the YP110 is also presented by Heller and Jasper:

Maximum Force Per Unit Length:

$$p_0 = \frac{3 \times 109{,}000}{2 \times 900}\left(1 + 4.7\right) = 1{,}036 \text{ lbs/in}$$

Maximum Effective Pressure at the Keel:

$$p_{01} = \frac{1036 \times 3}{96} = 32.4 \text{ psi}$$

Maximum Effective Pressure:

$$\overline{P} = 32.4 \times 1.1 = 35.64 \text{ psi}$$

This work is the foundation for most prediction methods. Other presentations of load calculation, measurement, or design can be found in the classification society publications cited in the reference section.

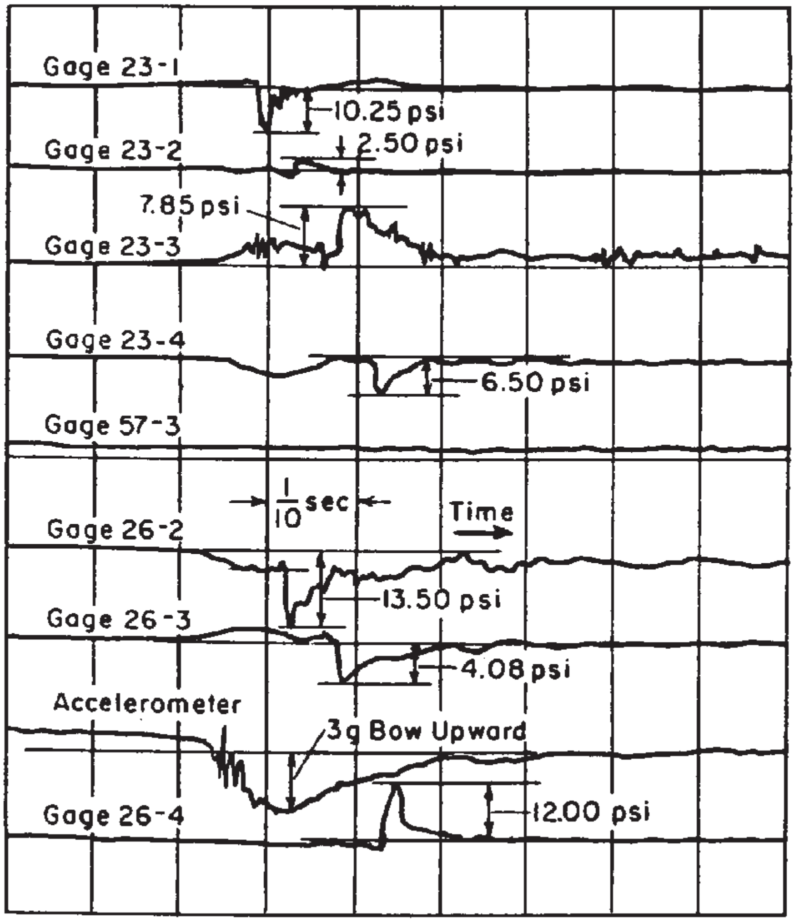


Figure 3-4 Pressures Recorded in Five and Six Foot Waves at a Speed of 28 Knots [Heller and Jasper, *On the Structural Design of Planing Craft*]

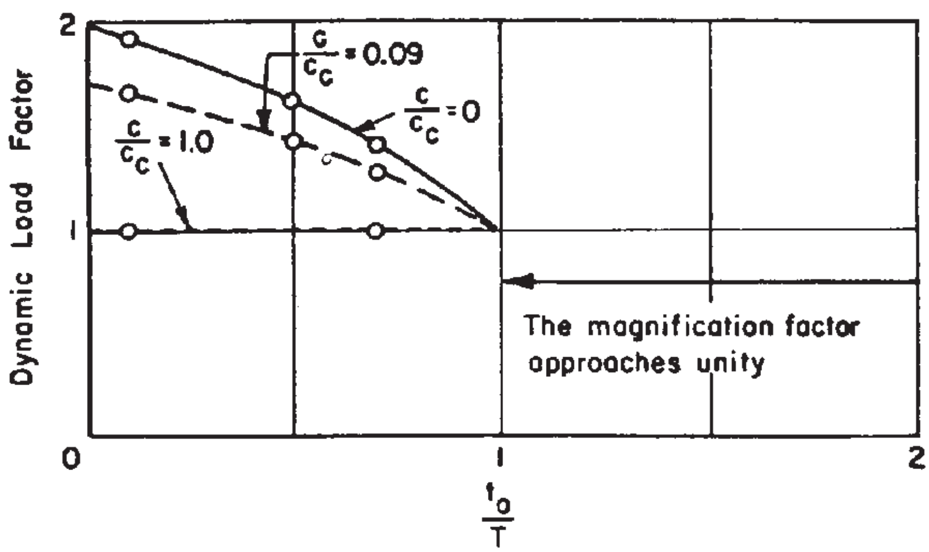


Figure 3-5 Dynamic Load factors for Typical Time Varying Impact Loads [Heller and Jasper, *On the Structural Design of Planing Craft*]

Load Distribution as a Function of Length

Classification society rules, such as the ABS Guide for High-Speed Craft (Oct, 1996 Draft) recognize that slamming loads vary as a function of distance along the waterline. Figures 3-6 and 3-7 show vertical acceleration factors used to calculate dynamic bottom pressures based on hull form and service factors, respectively. The general relationship given by the rules is as follows:

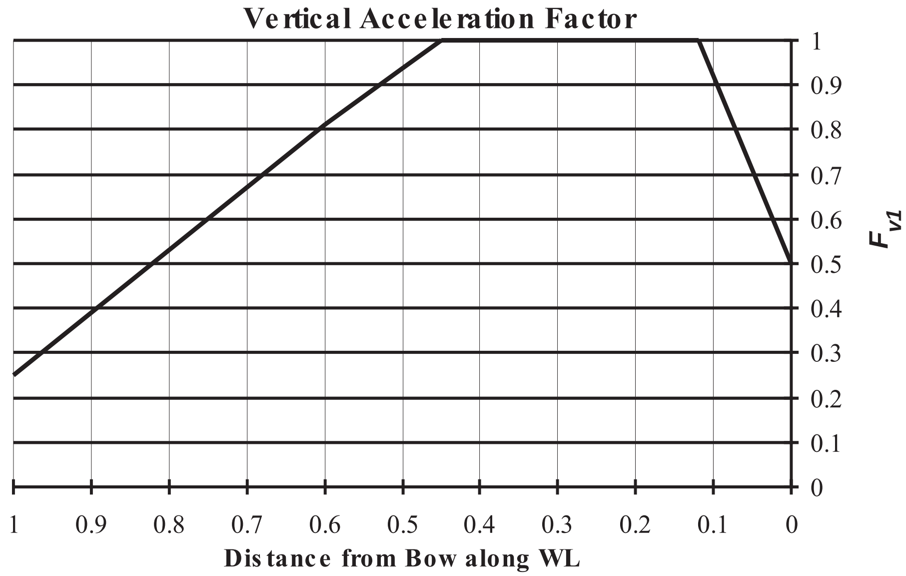


Figure 3-6 Vertical Acceleration Factor as a Function of Distance from Bow, F_{v1}, Used in ABS Calculations

$$Pressure_b \approx \frac{\Delta}{L_{wl}\ B} F_{v1} \tag{3-5}$$

and

$$Pressure_i \approx N\ d\, F_{v2} \tag{3-6}$$

where:

Δ = displacement

L_{wl} = waterline length

B = beam

N = service factor

d = draft

The rules require that the higher pressure calculated be used as the design pressure for planing and semi-planing craft. The reader is instructed to consult the published rules to get the exact equations with additional factors to fit hull geometry and engineering units used.

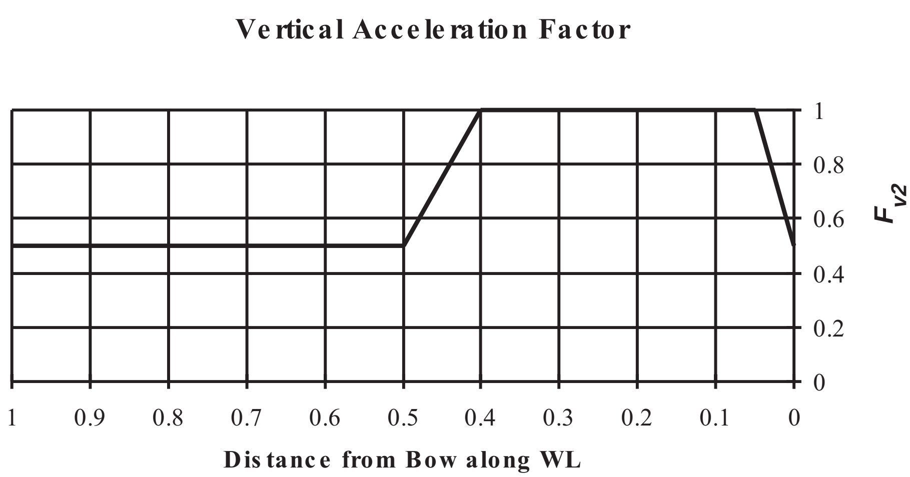


Figure 3-7 Vertical Acceleration Factor as a Function of Distance from Bow, F_{v2}, Used in ABS Calculations

Slamming Area Design Method

NAVSEA's *High Performance Marine Craft Design Manual Hull Structures* [3-9] prescribes a method for calculating longitudinal shear force and bending moments based on assigning a slamming pressure area extending from the keel to the turn of the bilge and centered at the longitudinal center of gravity (LCG). This area is calculated as follows:

$$A_R = \frac{25\,\Delta}{T}\ (\text{ft}^2) \qquad (3\text{-}7a)$$

$$A_R = \frac{0.7\,\Delta}{T}\ (\text{m}^2) \qquad (3\text{-}7b)$$

The slamming force is given as:

$$F_{sl} = \Delta\ \text{a}_\text{v} \qquad (3\text{-}8)$$

where:

Δ = Full load displacement in tons or tonnes

T = Molded draft in feet or meters

a_v = $\frac{1}{10}$ highest vertical acceleration at the LCG of the vessel

The vertical acceleration, a_v, is calculated for any position along the length of a monohull craft by the following expression:

$$a_v = \frac{k_v\ g_0\ V^{1.5}\left[\frac{H_s}{L}\right]}{1.697\ [1.0 + 0.04L]}\left[1 - \frac{\sqrt{L}}{2.6\ V}\right]\ (\text{ft/sec}^2) \qquad (3\text{-}9a)$$

$$a_v = \frac{k_v\ g_0\ V^{1.5}\left[\frac{H_s}{L}\right]}{1.697\ [1.0 + 0.012L]}\left[1 - \frac{\sqrt{L}}{4.71\ V}\right]\ (\text{m/sec}^2) \qquad (3\text{-}9b)$$

where:

H_s = Significant wave height (ft or m)

L = Vessel length (ft or m)

g_0 = Acceleration due to gravity

k_v = Longitudinal impact coefficient from Figure 3-8

V = Maximum vessel speed in knots in a sea state with significant wave height, H_s

The maximum bottom pressure, P_m, is given by:

$$P_m = 0.135\ T\ a_v\ \ (\text{psi}) \qquad (3\text{-}10a)$$

$$P_m = 10\ T\ a_v\ \ (\text{Mpa}) \qquad (3\text{-}10b)$$

The design pressure, P_d, for determining bottom panel scantling requirements is given by the expression:

$$P_d = F_a \times F_l \times P_m \qquad (3\text{-}11)$$

with F_a given in Figure 3-9 and F_l given in Figure 3-10. When using P_d to calculate loads on structural members, the following design areas should be used:

Structural Member	Design Area
Shell Plating	plate area (a × b)
Longitudinal Stiffener	unsupported stiffener length × stringer spacing
Transverse Stiffener	unsupported stiffener length × stiffener spacing
Structural Grillage	unsupported stringer length × unsupported stiffener length

Nonstandard Hull Forms

Hydrofoils, air-cushion vehicles and surface effect ships should be evaluated up on foils or on-cushion, as well as for hullborne operational states. Vertical accelerations for hydrofoils up on foils should not be less than 1.5 g_0.

Transverse bending moments for multihulls and SWATH vessels are the product of displacement, vertical acceleration and beam and often dictate major hull scantlings. Transverse vertical shear forces are the product of displacement and vertical acceleration only.

Model tests are often required to verify primary forces and moments for nonstandard hull forms. [3-9, 3-10]

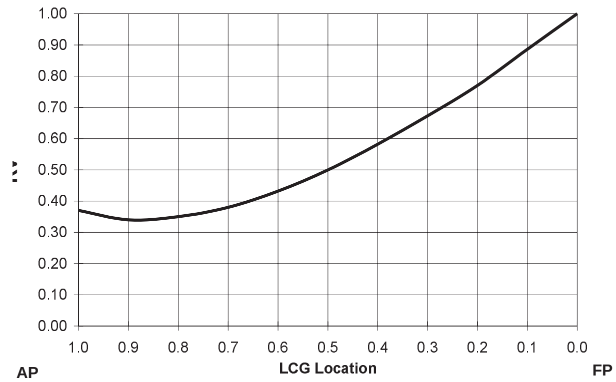


Figure 3-8 Longitudinal Impact Coefficient as a Function of Distance from Bow, k_V, Used in Vertical Acceleration Calculations [NAVSEA *High Performance Craft Design Manual*]

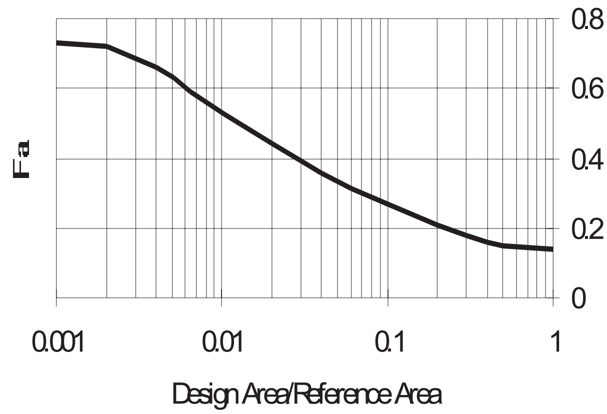


Figure 3-9 Design Area Coefficient Used in Design Pressure Calculations [NAVSEA *High Performance Craft Design Manual*]

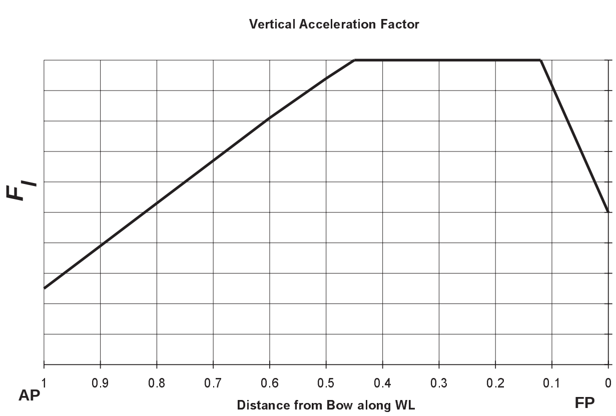


Figure 3-10 Longitudinal Pressure Distribution Used in Design Pressure Calculations [NAVSEA *High Performance Craft Design Manual*]

Hull Girder Stress Distribution

When the primary load forces act upon the hull structure as a long, slender beam, stress distribution patterns look like Figure 3-11 for the hogging condition with tension and compression interchanged for the sagging case. The magnitude of stress increases with distance from the neutral axis. On the other hand, shear stress is maximum at the neutral axis. Figure 3-12 shows the longitudinal distribution of principal stresses for a long, slender ship.

The relationship between bending moment and hull stress can be estimated from simple beam theory for the purposes of preliminary design. The basic relationship is stated as follows:

$$\sigma = \frac{M}{SM} = \frac{Mc}{I} \qquad (3\text{-}12)$$

where:

σ = unit stress

M = bending moment

SM = section modulus

c = distance to neutral axis

I = moment of inertia

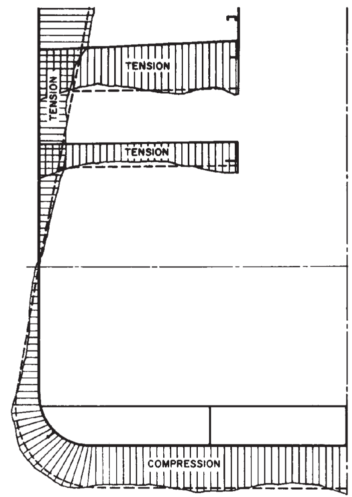


Figure 3-11 Theoretical and Measured Stress Distribution for a Cargo Vessel Midship Section [*Principles of Naval Architecture*]

The neutral axis is at the centroid of all longitudinal strength members, which for composite construction must take into account specific material properties along the ship's longitudinal axis. The actual neutral axis rarely coincides with the geometric center of the vessel's midship section. Hence, values for σ and c will be different for extreme fibers at the deck and hull bottom.

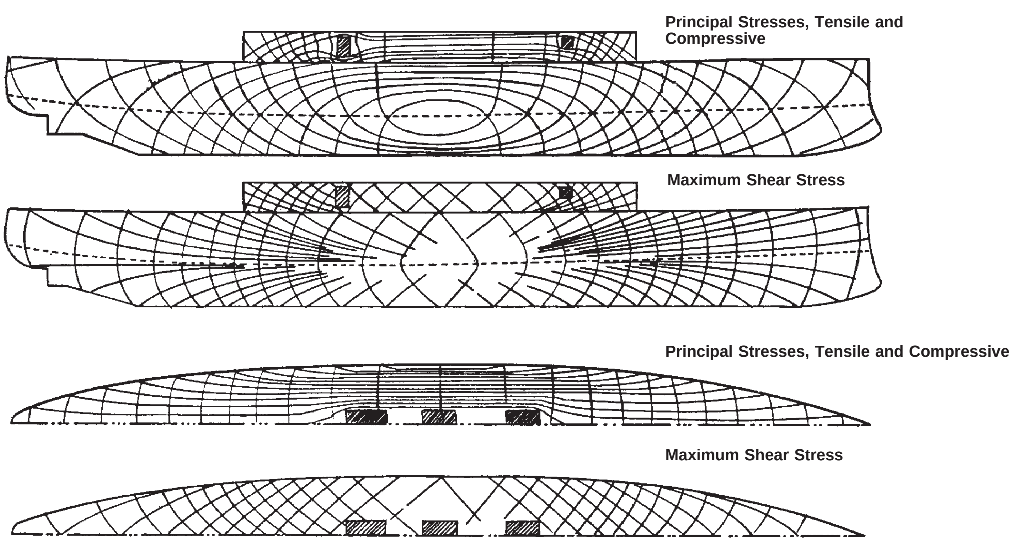


Figure 3-12 Longitudinal Distribution of Stresses in a Combatant [Hovgaard, *Structural Design of Warships*]

Lu & Jin have reported on an extensive design and test program that took place in China during the 1970's that involved a commercial hull form built using frame-stiffened, single-skin construction. Figure 3-13 shows the distribution of longitudinal strains and the arrangement of bending test strain gages used to verify the predicted hogging and sagging displacements of the 126 feet (38.5 meter) GRP hull studied. This study provided excellent insight into how a moderately-sized composite ship responds to hull girder loadings.

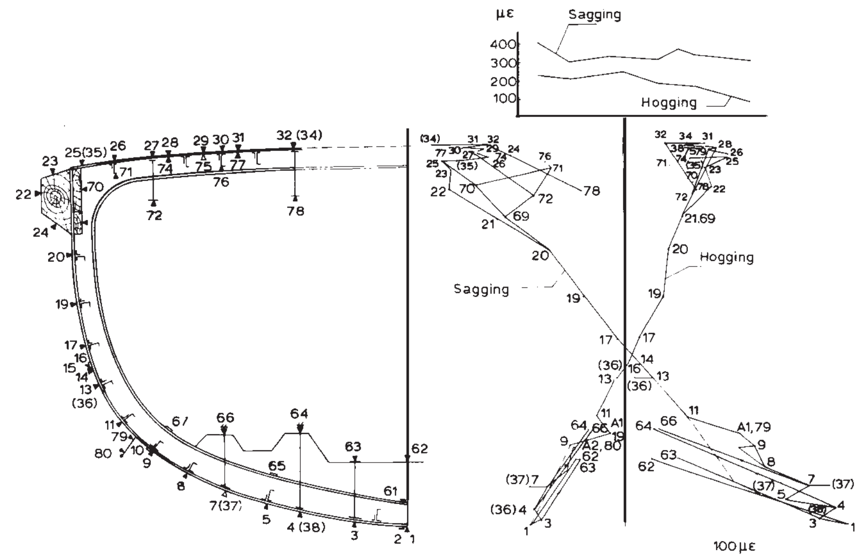


Figure 3-13 Distribution of Longitudinal Strains of a 38.5 Meter GRP Hull (above) and Longitudinal Strain Gage Location (below) [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," *Marine Structures*, Elsever, 1990]

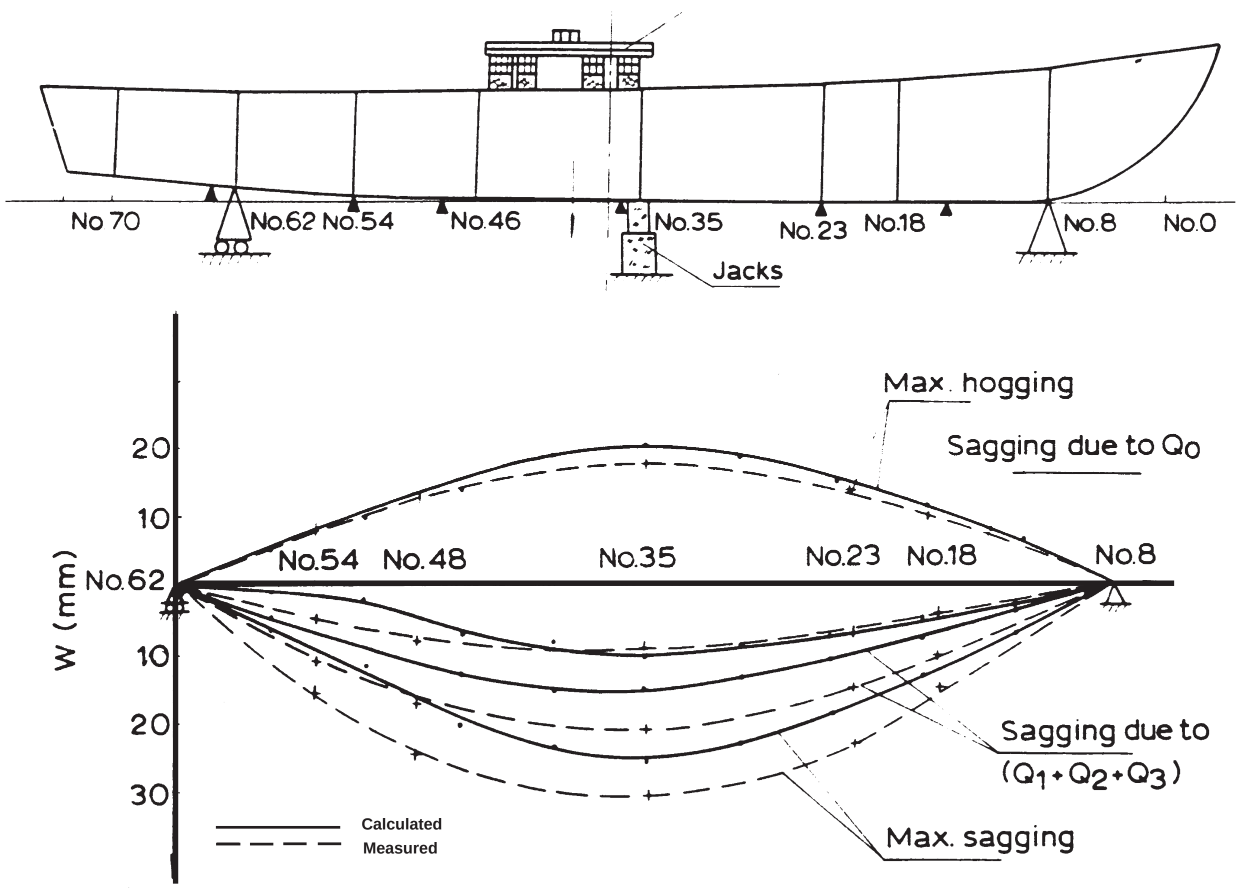


Figure 3-14 Predicted and Measured Vertical Displacements for a 38.5 Meter GRP Hull [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," *Marine Structures*, Elsever, 1990]

Other Hull and Deck Loads

Green water loading is used to calculate forces that hull side, topside and deck structure are exposed to in service. Green water loading is dependent on longitudinal location on the vessel and block coefficient (C_B) as well as the distance that a vessel will be from a safe harbor while in service. This methodology was originally published in the 1985 DnV *Rules for Classification of High Speed Light Craft*. [3-10]

Hull Side Structure, Topsides and Weather Decks

The design pressure used for designing side shell structure that is above the chine or turn of the bilge but below the designed waterline is given by DnV as:

$$p = 0.44\, h_0 = \left[k_l - \frac{1.5\, h_0}{T} \right] 0.0035\, L \text{ (psi)} \qquad (3\text{-}13a)$$

$$p = 10\, h_0 = \left[k_l - \frac{1.5\, h_0}{T} \right] 0.08\, L \text{ (Mpa)} \qquad (3\text{-}13b)$$

where:

h_0 = vertical distance from waterline to the load point

k_1 = longitudinal factor from Figure 3-15 based on C_B

$C_B = \dfrac{35\,\Delta}{L\,B\,T}$ (English units)

$= \dfrac{\Delta}{1.025\,L\,B\,T}$ (metric units)

B = greatest molded breadth at load waterline

For side shell above the waterline and deck structure, design pressure is given as:

$$p = a\, k_l\, (c\, L - 0.053\, h_0) \qquad (3\text{-}14)$$

where:

for topsides:
a = 0.044 (English)
= 1.00 (metric)

for decks:
a = 0.035 (English)
= 0.80 (metric)

with a minimum pressure of 1 psi (6.5 Mpa) for topeside structure and 0.75 psi (5.0 Mpa) for decks. Service factor, c, is:

c	Nautical Miles Out
0.080	> 45
0.072	≤ 45
0.064	≤ 15
0.056	≤ 5

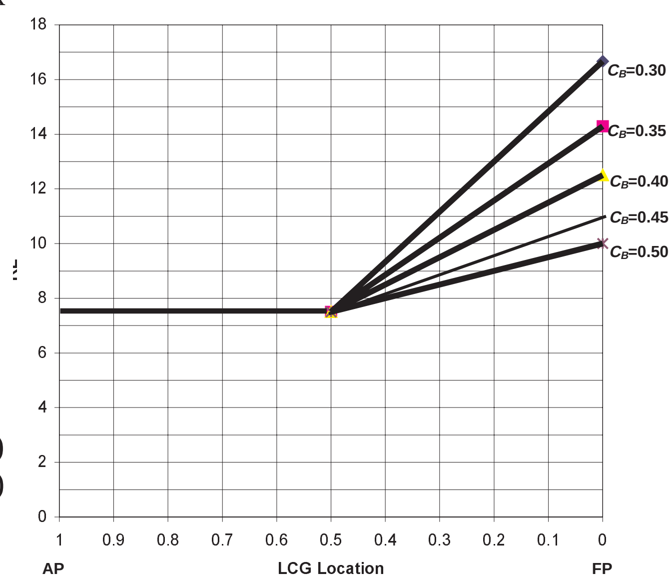


Figure 3-15 Green Water Distribution Factor, K_L [NAVSEA *High Performance Craft Design Manual*]

Deckhouses and Superstructures

For deckhouses and superstructure end bulkheads, the expression for design pressure is the same as for side shell structure above the waterline, where:

for lowest tier of superstructure not protected from weather:

$$a = 0.088 \text{ (English)}$$
$$= 2.00 \text{ (metric)}$$

for other superstructure and deckhouse front bulkheads:

$$a = 0.066 \text{ (English)}$$
$$= 1.50 \text{ (metric)}$$

for deckhouse sides:

$$a = 0.044 \text{ (English)}$$
$$= 1.00 \text{ (metric)}$$

elsewhere:

$$a = 0.035 \text{ (English)}$$
$$= 0.80 \text{ (metric)}$$

with a minimum pressure of 1.45 + 0.024 L psi (10 + 0.05 L Mpa) for lowest tier of superstructure not protected from weather and 0.725 + 0.012 L psi (5 + 0.025 L Mpa) elsewhere.

Compartment Flooding

Watertight bulkheads shall be designed to withstand pressures calculated by multiplying the vertical distance from the load point to the bulkhead top by the factor 0.44 (English units) or 10 (metric units) for collision bulkheads and 0.32 (English units) or 7.3 (metric units) for other watertight bulkheads.

Equipment & Cargo Loads

The design pressure from cargo and equipment are given by the expression:

$$p = 2.16 \times 10^{-3} (g_0 + 0.5\, a_v) \text{ (psi)} \quad \text{(3-15a)}$$

$$p = \rho H (g_0 + 0.5\, a_v) \text{ (Mpa)} \quad \text{(3-15b)}$$

For the metric expression, ρH = 1.6 for machinery space; 1.0 for weather decks; and 0.35 for accommodation spaces. ρ shall be 0.7 and H shall be the vertical distance from the load point to the above deck for sheltered decks or inner bottoms. [3-9, 3-10]

Mechanics of Composite Materials

The physical behavior of composite materials is quite different from that of most common engineering materials that are homogeneous and isotropic. Metals will generally have similar composition regardless of where or in what orientation a sample is taken. On the other hand, the makeup and physical properties of composites will vary with location and orientation of the principal axes. These materials are termed anisotropic, which means they exhibit different properties when tested in different directions. Some composite structures are, however, quasi-orthotropic, in their primary plane.

The mechanical behavior of composites is traditionally evaluated on both microscopic and macroscopic scale to take into account inhomogeneity. Micromechanics attempts to quantify the interactions of fiber and matrix (reinforcement and resin) on a microscopic scale on par with the diameter of a single fiber. Macromechanics treats composites as homogeneous materials, with mechanical properties representative of the laminate as a whole. The latter analytical approach is more realistic for the study of marine laminates that are often thick and laden with through-laminate inconsistencies. However, it is instructive to understand the concepts of micromechanics as the basis for macromechanic properties. The designer is again cautioned to verify all analytical work by testing builder's specimens.

Micromechanic Theory

General Fiber/Matrix Relationship

The theory of micromechanics was developed to help explain the complex mechanisms of stress and strain transfer between fiber and matrix within a composite. [3-11] Mathematical relationships have been developed whereby knowledge of constituent material properties can lead to laminate behavior predictions. Theoretical predictions of composite stiffness have traditionally been more accurate than predictions of ultimate strength. Table 3-1 describes the input and output variables associated with micromechanics.

Table 3-1 Micromechanics Concepts
[Chamis, ASM Engineers' Guide to Composite Materials]

Input	Output
Fiber Properties	Uniaxial Strengths
Matrix Properties	Fracture Toughness
Environmental Conditions	Impact Resistance
Fabrication Process Variables	Hygrothermal Effects
Geometric Configuration	

The basic principles of the theory can be illustrated by examining a composite element under a uniaxial force. Figure 3-16 shows the state of stress and transfer mechanisms of fiber and matrix when subjected to pure tension. On a macroscopic scale, the element is in simple tension, while internally a number of stresses can be present. Represented in Figure 3-16 are compressive stresses (vertical arrows pointing inwards) and shear stresses (thinner arrows along the fiber/matrix interface). This combined stress state will determine the failure point of the material. The bottom illustration in Figure 3-16 is representative of a poor fiber/matrix bond or void within the laminate. The resulting imbalance of stresses between the fiber and matrix can lead to local instability, causing the fiber to shift or buckle. A void along 1% of the fiber surface generally reduces interfacial shear strength by 7%. [3-11]

Fiber Orientation

Orientation of reinforcements in a laminate is widely known to dramatically effect the mechanical performance of composites. Figure 3-17 is presented to understand tension failure mechanisms in unidirectional composites on a microscopic scale. Note that at an angle of 0°, the strength of the composite is almost completely dependent on fiber tensile strength. The following equations refer to the three failure mechanisms shown in Figure 3-17:

Fiber tensile failure:

$$\sigma_c = \sigma \qquad (3\text{-}16)$$

Matrix or interfacial shear:

$$\tau = \sigma \sin\Phi \cos\Phi \qquad (3\text{-}17)$$

Composite tensile failure:

$$\sigma_u = \sigma \sin\Phi \qquad (3\text{-}18)$$

where:

σ_c = composite tensile strength

σ = applied stress

Φ = angle between the fibers and tensile axis

τ = shear strength of the matrix or interface

σ_u = tensile strength of the matrix

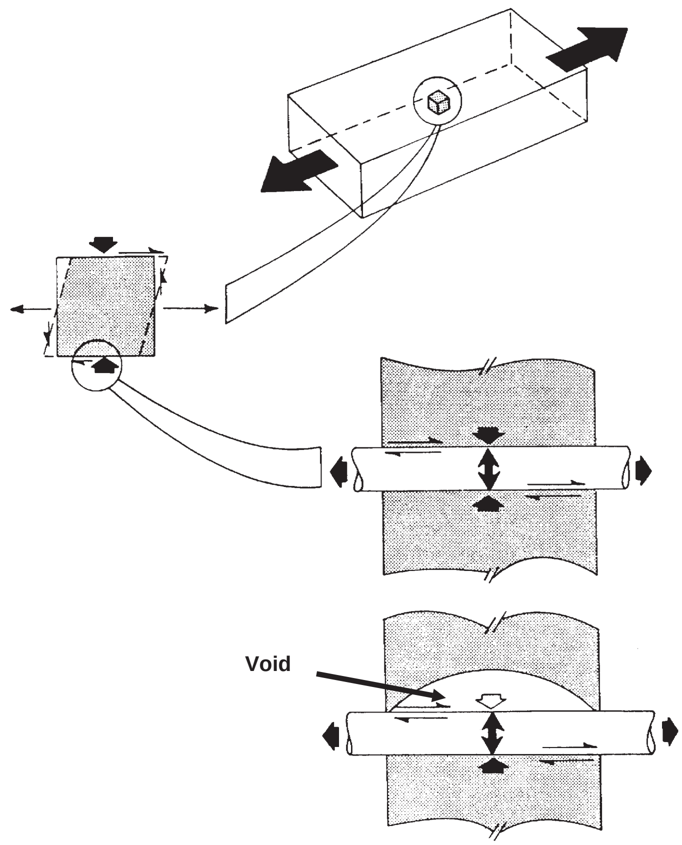


Figure 3-16 State of Stress and Stress Transfer to Reinforcement [*Material Engineering*, May, 1978 p. 29]

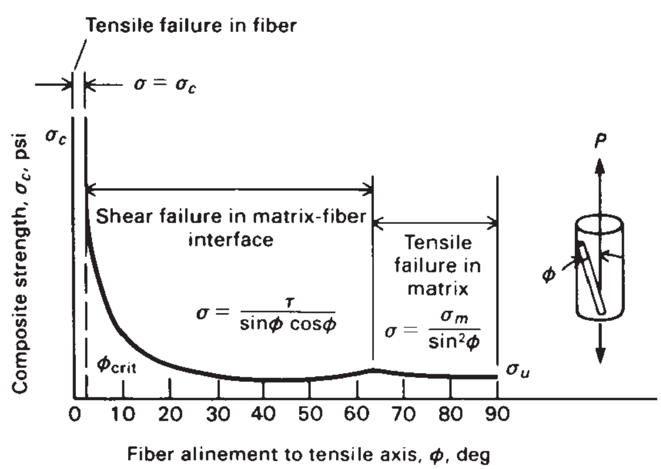


Figure 3-17 Failure Mode as a Function of Fiber Alignment [*ASM Engineers' Guide to Composite Materials*]

Micromechanics Geometry

Figure 3-18 shows the orientation and nomenclature for a typical fiber composite geometry. Properties along the fiber or *x* direction (1-axis) are called longitudinal; transverse or *y* (2-axis) are called transverse; and in-plane shear (1-2 plane) is also called intralaminar shear. The through-thickness properties in the *z* direction (3-axis) are called interlaminar. Ply properties are typically denoted with a letter to describe the property with suitable subscripts to describe the constituent material, plane, direction and sign (with strengths). As an example, S_{m11T} indicates matrix longitudinal tensile strength.

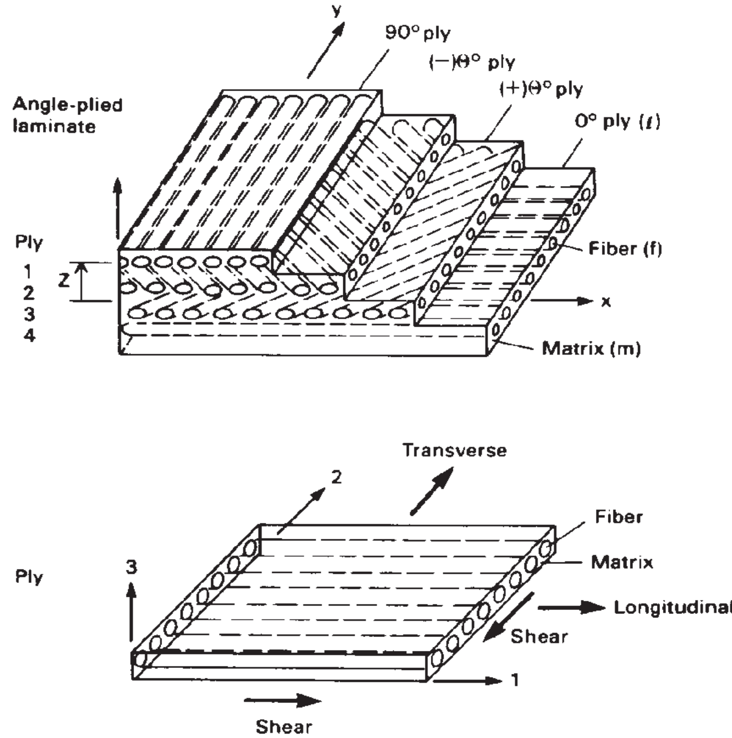


Figure 3-18 Fiber Composite Geometry [Chamis, *ASM Engineers' Guide to Composite Materials*]

The derivation of micromechanics equations is based on the assumption that: 1) the ply and its constituents behave linearly elastic until fracture (see Figure 3-19), 2) bonding is complete between fiber and matrix and 3) fracture occurs in one of the following modes: a) longitudinal tension, b) fiber compression, c) delamination, d) fiber microbuckling, e) transverse tension, or f) intralaminar shear. [3-2] The following equations describe the basic geometric relationships of composite micromechanics:

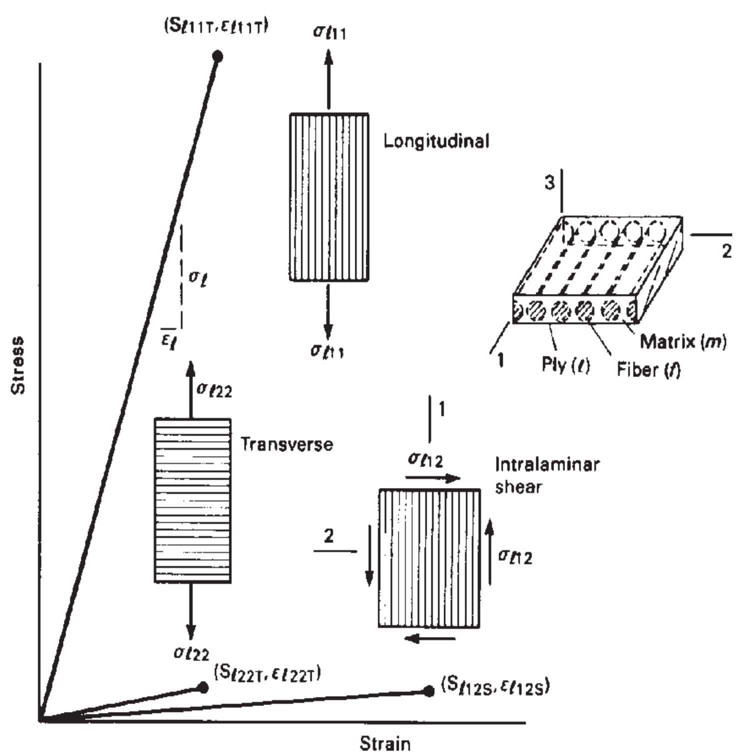


Figure 3-19 Typical Stress-Strain Behavior of Unidirectional Fiber Composites [Chamis, *ASM Engineers' Guide to Composite Materials*]

Partial volumes:

$$k_f + k_m + k_v = 1 \qquad (3\text{-}19)$$

Ply density:

$$\rho_l = k_f \rho_f + k_m \rho_m \qquad (3\text{-}20)$$

Resin volume ratio:

$$k_m = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_m}{\rho_f}\right)\left(\frac{1}{\lambda_m} - 1\right)\right]} \qquad (3\text{-}21)$$

Fiber volume ratio:

$$k_f = \frac{(1 - k_v)}{\left[1 + \left(\frac{\rho_f}{\rho_m}\right)\left(\frac{1}{\lambda_f} - 1\right)\right]} \qquad (3\text{-}22)$$

Weight ratio:

$$\lambda_f + \lambda_m = 1 \qquad (3\text{-}23)$$

where:

f = fiber
m = matrix
v = void
l = ply
λ = weight percent

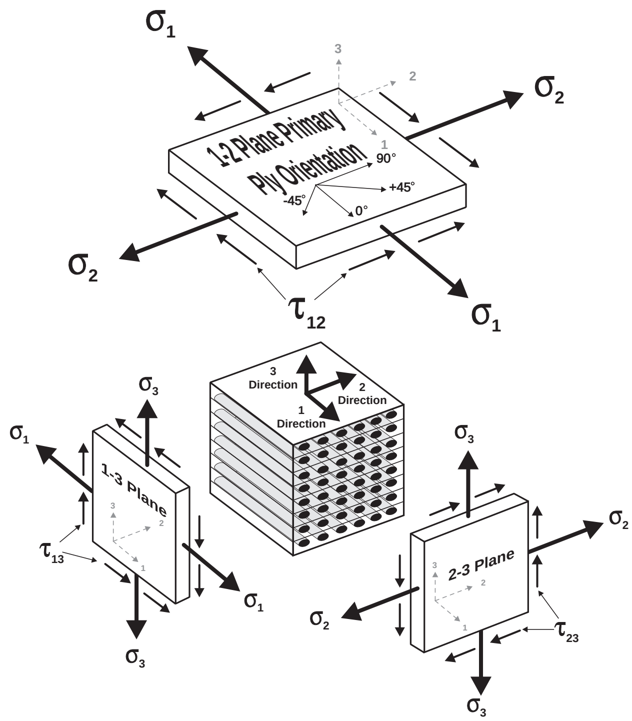


Figure 3-20 Notation Typically Used to Describe Ply Properties

Elastic Constants

The equations for relating elastic moduli and Poisson's ratios are given below. Properties in the 3-axis direction are the same as the 2-axis direction because the ply is assumed transversely isotropic in the 2-3 plane (see bottom illustration of Figure 3-18).

Longitudinal modulus:

$$E_{l\,11} = k_f\, E_{f\,11} + k_m E_m \qquad (3\text{-}24)$$

Transverse modulus:

$$E_{l\,22} = \frac{E_m}{1 - \sqrt{k_f}\left(1 - \frac{E_m}{E_{f\,22}}\right)} = E_{l\,33} \qquad (3\text{-}25)$$

Shear modulus:

$$G_{l\,12} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f\,12}}\right)} = G_{l\,13} \qquad (3\text{-}26)$$

$$G_{l\,23} = \frac{G_m}{1 - \sqrt{k_f}\left(1 - \frac{G_m}{G_{f\,23}}\right)} = G_{l\,13} \qquad (3\text{-}27)$$

Poisson's ratio:

$$\nu_{l\,12} = k_f\ \nu_{l\,12} + k_m\, \nu_m = \nu_{l\,13} \qquad (3\text{-}28)$$

In-Plane Uniaxial Strengths

The equations for approximating composite strength properties are based on the fracture mechanisms outlined above under micromechanics geometry. Three of the fracture modes fall under the heading of longitudinal compression. It should be emphasized that prediction of material strength properties is currently beyond the scope of simplified mathematical theory. The following approximations are presented to give insight into which physical properties dominate particular failure modes.

Approximate longitudinal tension:

$$S_{l\,11T} \approx k_f \, S_{f\,T} \tag{3-29}$$

Approximate fiber compression:

$$S_{l\,11C} \approx k_f \, S_{f\,C} \tag{3-30}$$

Approximate delamination/shear:

$$S_{l\,11C} \approx 10\, S_{l\,12S} + 2.5 S_{m\,T} \tag{3-31}$$

Approximate microbuckling:

$$S_{l\,11C} \approx \frac{G_m}{1 - k_f\left(1 - \dfrac{G_m}{G_{f\,12}}\right)} \tag{3-32}$$

Approximate transverse tension:

$$S_{l\,22T} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f\,22}}\right)\right] S_{mT} \tag{3-33}$$

Approximate transverse compression:

$$S_{l\,22C} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{E_m}{E_{f\,22}}\right)\right] S_{mC} \tag{3-34}$$

Approximate intralaminar shear:

$$S_{l\,12S} \approx \left[1 - \left(\sqrt{k_f} - k_f\right)\left(1 - \frac{G_m}{G_{f\,12}}\right)\right] S_{mS} \tag{3-35}$$

Approximate void influence on matrix:

$$S_m \approx \left\{1 - \left[\frac{4k_v}{(1 - k_f)\,\pi}\right]^{1/2}\right\} S_m \tag{3-36}$$

Through-Thickness Uniaxial Strengths

Estimates for properties in the 3-axis direction are given by the equations below. Note that the interlaminar shear equation is the same as that for in-plane. The short beam shear depends heavily on the resin shear strength and is about 1½ times the interlaminar value. Also, the longitudinal flexural strength is fiber dominated while the transverse flexural strength is more sensitive to matrix strength.

Approximate interlaminar shear:

$$S_{l\,13S} \approx \left[1-\left(\sqrt{k_f}-1\right)\left(1-\frac{G_m}{G_{f\,12}}\right)\right] S_{mS} \qquad (3\text{-}37)$$

$$S_{l\,23S} \approx \left[\frac{1-\sqrt{k_f}\left(1-\frac{G_m}{G_{f\,23}}\right)}{1-k_f\left(1-\frac{G_m}{G_{f\,23}}\right)}\right] S_{mS} \qquad (3\text{-}38)$$

Approximate flexural strength:

$$S_{l\,11F} \approx \frac{3\,k_f\,S_{f\,T}}{1+\frac{S_{f\,T}}{S_{f\,C}}} \qquad (3\text{-}39)$$

$$S_{l\,22F} \approx \frac{3\left[1-\left(\sqrt{k_f}-k_f\right)\left(1-\frac{E_m}{E_{f\,22}}\right)\right] S_{m\,T}}{1+\frac{S_{m\,T}}{S_{m\,C}}} \qquad (3\text{-}40)$$

Approximate short-beam shear:

$$S_{l\,13SB} \approx 1.5\, S_{l\,13S} \qquad (3\text{-}41)$$

$$S_{l\,23SB} \approx 1.5\, S_{l\,23S} \qquad (3\text{-}42)$$

Uniaxial Fracture Toughness

Fracture toughness is an indication of a composite material's ability to resist defects or discontinuities such as holes and notches. The fracture modes of general interest include: opening mode, in-plane shear and out-of-plane shear. The equations to predict longitudinal, transverse and intralaminar shear fracture toughness are beyond the scope of this text and can be found in the cited reference. [3-2]

In-Plane Uniaxial Impact Resistance

The impact resistance of unidirectional composites is defined as the in-plane uniaxial impact energy density. The five densities are: longitudinal tension and compression; transverse tension and compression; and intralaminar shear. The reader is again directed to reference [3-2] for further elaboration.

Through-Thickness Uniaxial Impact Resistance

The through-thickness impact resistance is associated with impacts normal to the surface of the composite, which is generally of particular interest. The energy densities are divided as follows: longitudinal interlaminar shear, transverse interlaminar shear, longitudinal flexure, and transverse flexure. The derivation of equations and relationships for this and the remaining micromechanics phenomena can be found in reference [3-2].

Thermal
The following thermal behavior characteristics for a composite are derived from constituent material properties: heat capacity, longitudinal conductivity, and longitudinal and transverse thermal coefficients of expansion.

Hygral Properties
The ply hygral properties predicted by micromechanics equation include diffusivity and moisture expansion. Additional equations have been derived to estimate moisture in the resin and composite as a function of the relative humidity ratio. An estimate for moisture expansion coefficient can be postulated analytically.

Hygrothermal Effects
The combined environmental effect of moisture and temperature is usually termed hygrothermal. All of the resin dominated properties are particularly influenced by hygrothermal phenomena. The degraded properties that are quantified include: glass transition temperature of wet resin, strength and stiffness mechanical characteristics, and thermal behavior.

Laminate Theory

Laminae or Plies
The most elementary level considered by macromechanic theory is the lamina or ply. This consists of a single layer of reinforcement and associated volume of matrix material. In aerospace applications, all specifications are expressed in terms of ply quantities. Marine applications typically involve thicker laminates and are usually specified according to overall thickness, especially when successive plies are identical.

For most polymer matrix composites, the reinforcement fiber will be the primary load carrying element because it is stronger and stiffer than the matrix. The mechanism for transferring load throughout the reinforcement fiber is the shearing stress developed in the matrix. Thus, care must be exercised to ensure that the matrix material does not become a strain limiting factor. As an extreme example, if a polyester reinforcement with an ultimate elongation of about 20% was combined with a polyester resin with 1.5% elongation to failure, cracking of the resin would occur before the fiber was stressed to a level that was 10% of its ultimate strength.

Laminates
A laminate consists of a series of laminae or plies that are bonded together with a material that is usually the same as the matrix of each ply. Indeed, with contact molding, the wet-out and laminating processes are continuous operations. A potential weak area of laminates is the shear strength between layers of a laminate, especially when the entire lamination process is not continuous.

A major advantage to design and construction with composites is the ability to vary reinforcement material and orientation throughout the plies in a laminate. In this way, the physical properties of each ply can be optimized to resist the loading on the laminate as a whole, as well as the out-of-plane (through thickness) loads that create unique stress fields in each ply. Figure 3-21 illustrates the concept of stress field discontinuity within a laminate.

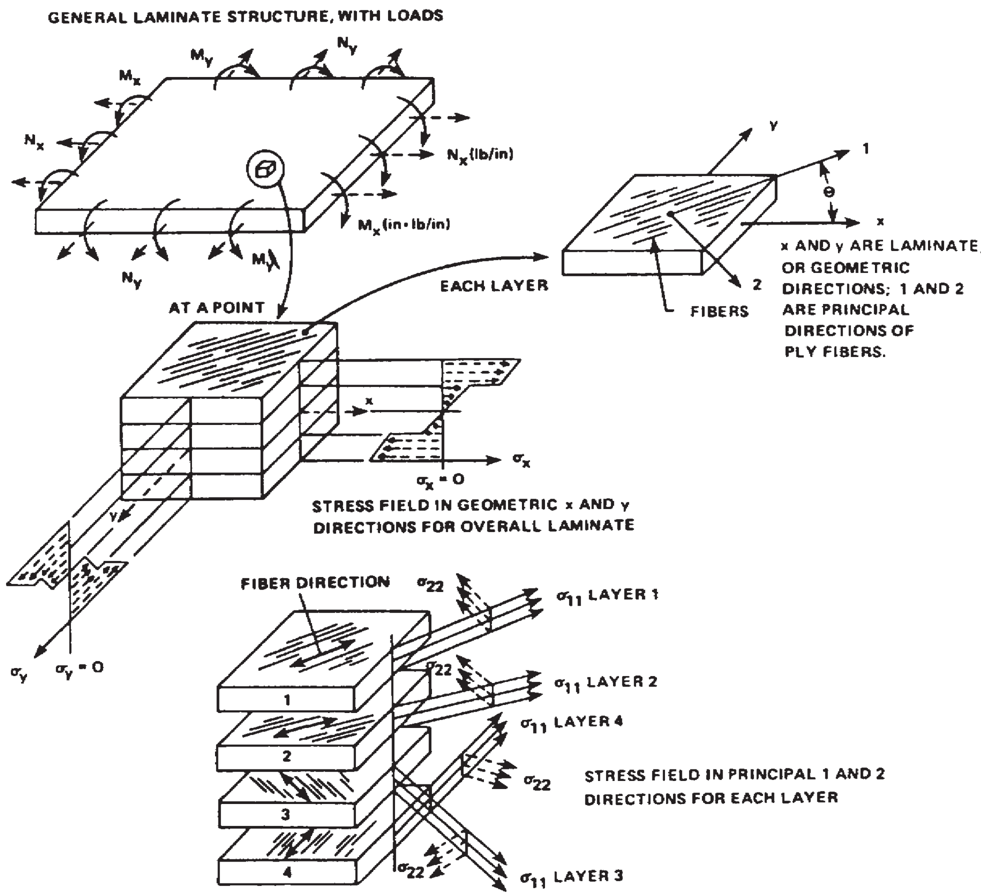


Figure 3-21 Elastic Properties of Plies within a Laminate [Schwartz, *Composite Materials Handbook*]

Laminate Properties

Predicting the physical properties of laminates based on published data for the longitudinal direction (1-axis) is not very useful, as this data was probably derived from samples fabricated in a very controlled environment. Conditions under which marine laminates are fabricated can severely limit the resultant mechanical properties. To date, safety factors have generally been sufficiently high to prevent widespread failure. However, instances of stress concentrations, resin-rich areas and voids can negate even large safety factors.

There are essentially three ways in use today to predict the behavior of a laminated structure under a given loading scenario. In all cases, estimates for Elastic properties are more accurate than those for Strength properties. This is in part due to the variety of failure mechanisms involved. The analytical techniques currently in use include:

- Property charts called "carpet plots" that provide mechanical performance data based on orientation composition of the laminate;
- Laminate analysis software that allows the user to build a laminate from a materials database and view the stress and strain levels within and between plies in each of the three mutually perpendicular axes; and
- Test data based on identical laminates loaded in a similar fashion to the design case.

Carpet Plots

Examples of carpet plots based on a carbon fiber/epoxy laminate are shown in Figures 3-22, 3-23 and 3-24 for modulus, Poisson's ratio, and strength respectively. The bottom axis shows the percentage of ±45° reinforcement. "Iso" lines within the graphs correspond to the percentage of 0° and 90° reinforcement. The resultant mechanical properties are based on the assumption of uniaxial loading (hence, values are for longitudinal properties only) and assume a given design temperature and design criterion (such as B-basis where there is 90% confidence that 95% of the failures will exceed the value). [3-2] Stephen Tsai, an acknowledged authority on composites design, has dismissed the use of carpet plot data in favor of the more rigorous laminated plate theory. [3-12]

Carpet plots have been a common preliminary design tool within the aerospace industry where laminates typically consist of a large number of thin plies. Additionally, out-of-plane loads are not of primary concern as is the case with marine structures. An aerospace designer essentially views a laminate as a homogeneous engineering material with some degraded mechanical properties derived from carpet plots. Typical marine laminates consist of much fewer plies that are primarily not from unidirectional reinforcements. Significant out of plane loading and high aspect ratio structural panels render the unidirectional data from carpet plots somewhat meaningless for designing FRP marine structures.

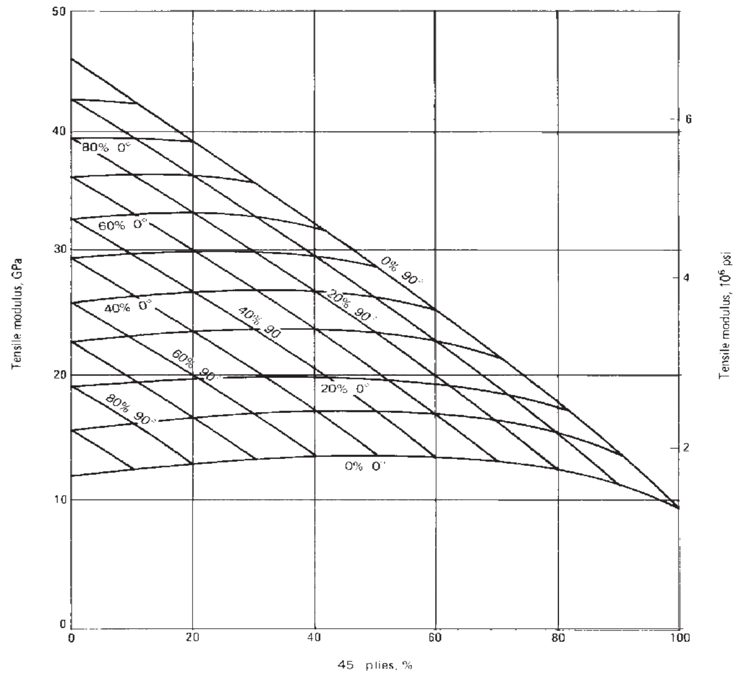


Figure 3-22 Carpet Plot Illustrating Laminate Tensile Modulus [*ASM Engineered Materials Handbook*]

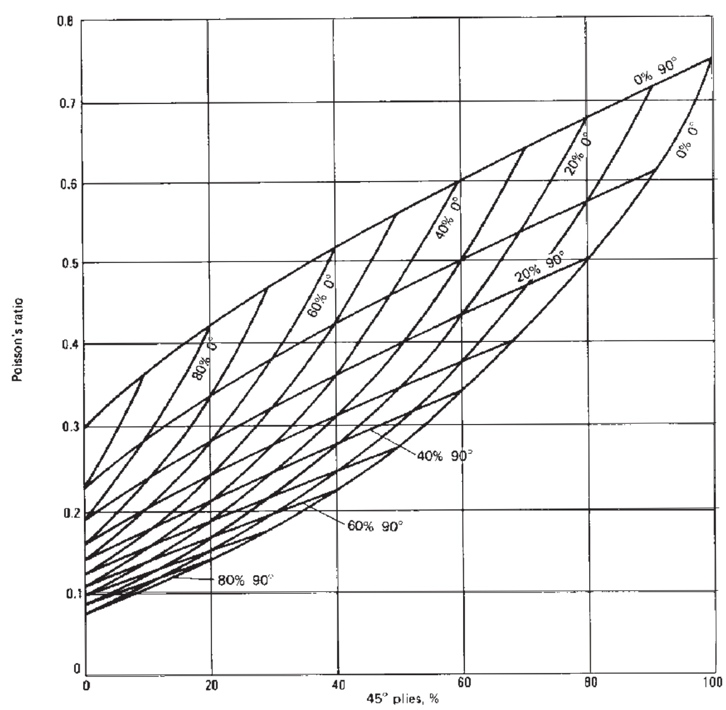


Figure 3-23 Carpet Plot Illustrating Poisson's Ratio [*ASM Engineered Materials Handbook*]

Computer Laminate Analysis

There are a number of structural analysis computer programs available for workstations or advanced PC computers that use finite-element or finite-difference numerical methods and are suitable for evaluating composites. In general, these programs will address:

- Structural response of laminated and multidirectional reinforced composites;
- Changes in material properties with temperature, moisture and ablative decomposition;
- Thin-shelled, thick-shelled, and/or plate structures;
- Thermal-, pressure- traction-, deformation- and vibration-induced load states;
- Failure modes;
- Non-linearity;
- Structural instability; and
- Fracture mechanics.

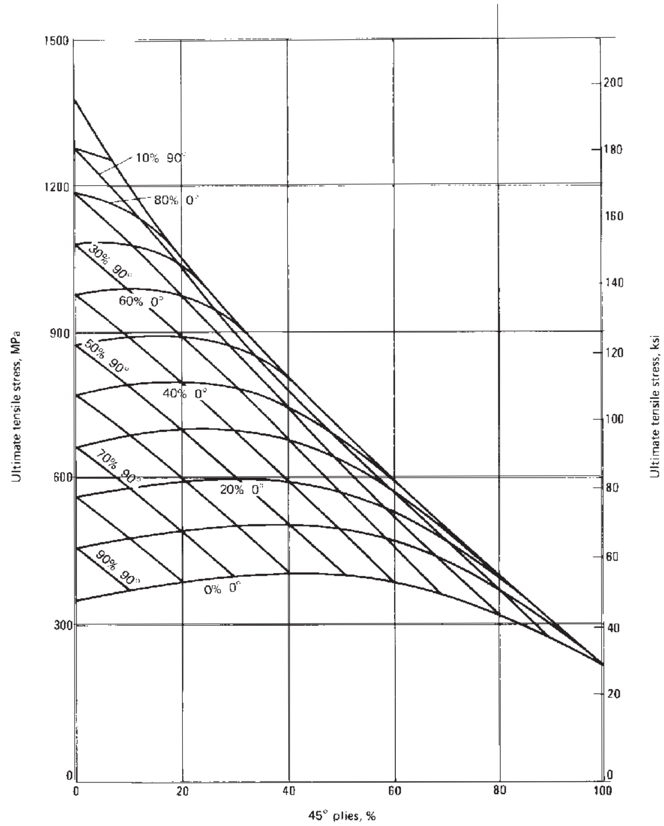


Figure 3-24 Carpet Plot Illustrating Tensile Strength [*ASM Engineered Materials Handbook*]

The majority of these codes for mainframes are quite expensive to acquire and operate, which precludes their use for general marine structures. Specialized military applications such as a pressure hull for a torpedo or a highly stressed weight critical component might justify analysis with these sort of programs. [3-2]

More useful to the marine designer, are the PC-based laminate analysis programs that allow a number of variations to be evaluated at relatively low cost. The software generally costs less than $500 and can run on hardware that is probably already integrated into a design office. The better programs are based on laminated plate theory and do a reasonable job of predicting first ply failure in strain space. Prediction of ultimate strengths with materials that enter non-elastic regions, such as foam cores, will be of limited accuracy. Some other assumptions in laminated plate theory include: [3-2]

- The thickness of the plate is much smaller than the in-plane dimensions;
- The strains in the deformed region are relatively small;
- Normal to the undeformed plate surface remain normal to the deformed plate surface;
- Vertical deflection does not vary through the thickness; and
- Stress normal to the plate surface is negligible.

For a detailed description of laminated plate theory, the reader is advised to refer to ***Introduction to Composite Materials***, by S.W. Tsai and H.T. Hahn, Technomic, Lancaster, PA (1985).

Table 3-2 illustrates a typical range of input and output variables for computer laminate analysis programs. Some programs are menu driven while others follow a spreadsheet format. Once material properties have been specified, the user can "build" a laminate by selecting materials and orientation. As a minimum, stresses and strain failure levels for each ply will be computed. Some programs will show stress and strain states versus design allowables based on various failure criteria. Most programs will predict which ply will fail first and provide some routine for laminate optimization. In-plane loads can usually be entered to compute predicted states of stress and strain instead of failure envelopes.

Table 3-2 Typical Input and Output Variables for Laminate Analysis Programs

Input		Output	
Load Conditions	**Material Properties**	**Ply Properties**	**Laminate Response**
Longitudinal In-Plane Loads	Modulus of Elasticity	Thicknesses*	Longitudinal Deflection
Transverse In-Plane Loads	Poisson's Ratio	Orientation*	Transverse Deflection
Vertical In-Plane Loads (shear)	Shear Modulus	Fiber Volume*	Vertical Deflection
Longitudinal Bending Moments	Longitudinal Strength	Longitudinal Stiffness	Longitudinal Strain
Transverse Bending Moments	Transverse Strength	Transverse Stiffness	Transverse Strain
Vertical Moments (torsional)	Shear Strength	Longitudinal Poisson's Ratio	Vertical Strain
Failure Criteria	Thermal Expansion Coefficients	Transverse Poisson's Ratio	Longitudinal Stress per Ply
Temperature Change		Longitudinal Shear Modulus	Transverse Stress per Ply
		Transverse Shear Modulus	Vertical Stress (shear) per Ply
			First Ply to Fail
			Safety Factors
*These ply properties are usually treated as input variables			

Failure Criteria

Failure criteria used for analysis of composites structures are similar to those in use for isotropic materials, which include maximum stress, maximum strain and quadratic theories. [3-12] These criteria are empirical methods to predict failure when a laminate is subjected to a state of combined stress. The multiplicity of possible failure modes (i.e. fiber vs. laminate level) prohibits the use of a more rigorously derived mathematical formulation. Specific failure modes are described in Chapter Four. The basic material data required for two-dimensional failure theory is longitudinal and transverse tensile, and compressive as well as longitudinal shear strengths.

Maximum Stress Criteria

Evaluation of laminated structures using this criteria begins with a calculation of the strength/stress ratio for each stress component. This quantity expresses the relationship between the maximum, ultimate or allowable strength, and the applied corresponding stress. The lowest ratio represents the mode that controls ply failure. This criteria ignores the complexities of composites failure mechanisms and the associated interactive nature of the various stress components.

Maximum Strain Criteria

The maximum strain criteria follows the logic of the maximum stress criteria. The maximum strain associated with each applied stress field is calculated by dividing strengths by moduli of elasticity, when this is known for each ply. The dominating failure mode is that which produces the highest strain level. Simply stated, failure is controlled by the ply that first reaches its elastic limit. This concept is important to consider when designing hybrid laminates that contain low strain materials, such as carbon fiber. Both the maximum stress and maximum strain criteria can be visualized in two-dimensional space as a box with absolute positive and negative values for longitudinal and transverse axes. This failure envelope implies no interaction between the stress fields and material response. Structural design considerations (strength vs. stiffness) will dictate whether stress or strain criteria is more appropriate.

Quadratic Criteria for Stress and Strain Space

One way to include the coupling effects (Poisson phenomena) in a failure criteria is to use a theory based on distortional energy. The resultant failure envelope is an ellipse which is very oblong. A constant, called the normalized empirical constant, which relates the coupling of strength factors, generally falls between -½ (von Mises criteria) and 0 (modified Hill criteria). [3-12] A strain space failure envelope is more commonly used for the following reasons:

- Plotted data is less oblong;
- Data does not vary with each laminate;
- Input properties are derived more reliably; and
- Axes are dimensionless.

First- and Last-Ply to Failure Criteria

These criteria are probably more relevant with aerospace structures where laminates may consist of over 50 plies. The theory of first-ply failure suggests an envelope that describes the failure of the first ply. Analysis of the laminate continues with the contribution from that and successive plies removed. With the last ply to failure theory, the envelope is developed that corresponds to failure of the final ply in what is considered analogous to ultimate failure. Each of these concepts fail to take into account the contribution of a partially failed ply or the geometric coupling effects of adjacent ply failure.

Laminate Testing

Laminates used in the marine industry are typically characterized using standard ASTM tests. Multiple laminates, usually a minimum of ⅛ inch (3 mm) thick, are used for testing and results are reported as a function of cross-sectional area, i.e. width × thickness. Thus, thickness of the laminate tested is a critical parameter influencing the reported data. High fiber laminates that are consolidated with vacuum pressure will be thinner than standard open mold laminates, given the same amount of reinforcement. Test data for these laminates will be higher, although load carrying capability may not be. The following ASTM tests were used to generate the laminate data presented in Appendix A. Comments regarding the application of these tests to typical marine laminates is also included. ISO and SACMA tests are also cited.

Tensile Tests

These test methods provide procedures for the evaluation of tensile properties of single-skin laminates. The tests are performed in the axial, or in-plane orientation. Properties obtained can include tensile strength, tensile modulus, elongation at break (strain to failure), and Poisson's ratio.

For most oriented fiber laminates, a rectangular specimen is preferred. Panels fabricated of resin alone (resin casting) or utilizing randomly oriented fibers (such as chopped strand) may be tested using dog-bone (dumbbell) type specimens. Care must be taken when cutting test specimens to assure that the edges are aligned in the axis under test. The test axis or orientation must be specified for all oriented-fiber laminates.

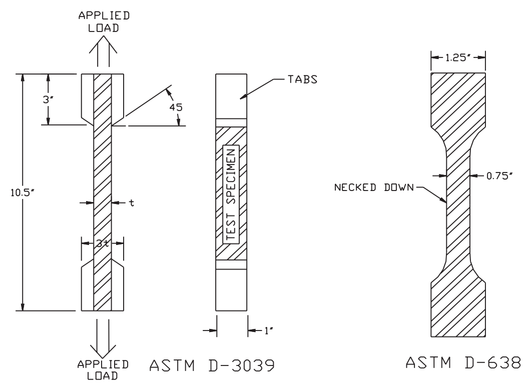


Figure 3-25 Test Specimen Configuration for ASTM D-3039 and D-638 Tensile Tests (Structural Composites, Inc.)

Tensile Test Methods	
ASTM D 3039	Tensile Properties of Polymer Matrix Composite Materials Specimen Type: Rectangular, with tabs
ASTM D 638	Tensile Properties of Plastics Specimen Type: Dumbbell
ISO 3268	Plastics - Glass-Reinforced Materials - Determination of Tensile Properties Specimen Type: Type I Dumbbell Type II Rectangular, no tabs Type III Rectangular, with tabs
SACMA SRM 4	Tensile Properties of Oriented Fiber-Resin Composites Specimen Type: Rectangular, with tabs
SACMA SRM 9	Tensile Properties of Oriented Cross-Plied Fiber-Resin Composites Specimen Type: Rectangular, with tabs

Compressive Tests

Several methods are available for determination of the axial (in-plane, edgewise, longitudinal) compression properties. The procedures shown are applicable for single-skin laminates. Other methods are utilized for determination of "edgewise" and "flatwise" compression of sandwich composites. Properties obtained can include compressive strength and compressive modulus.

For most oriented fiber laminates, a rectangular specimen is preferred. Panels fabricated of randomly oriented fibers such as chopped strand may be tested using dog-bone (dumbbell) type specimens.

Compressive Test Methods	
ASTM D 3410	Compressive Properties of Unidirectional or Crossply Fiber-Resin Composites Specimen Type: Rectangular, with tabs
ASTM D 695	Compressive Properties of Rigid Plastics Specimen Type: Rectangular or dumbbell
ISO 604	Plastics - Determination of Compressive Properties Specimen Type: Rectangular
SACMA SRM 1	Compressive Properties of Oriented Fiber-Resin Composites Specimen Type: Rectangular, with tabs
SACMA SRM 6	Compressive Properties of Oriented Cross-Plied Fiber-ResinComposites Specimen Type: Rectangular, with tabs

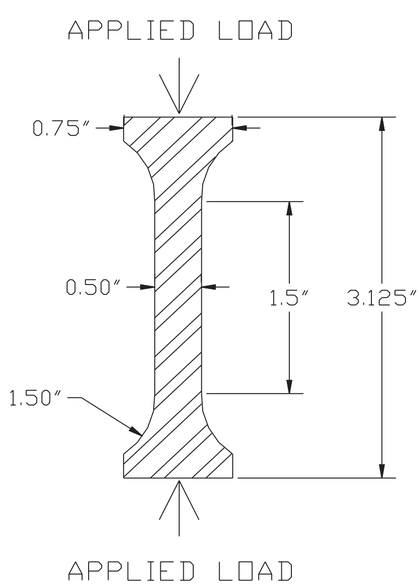


Figure 3-26 Test Specimen Configuration for ASTM D-695 Compression Test

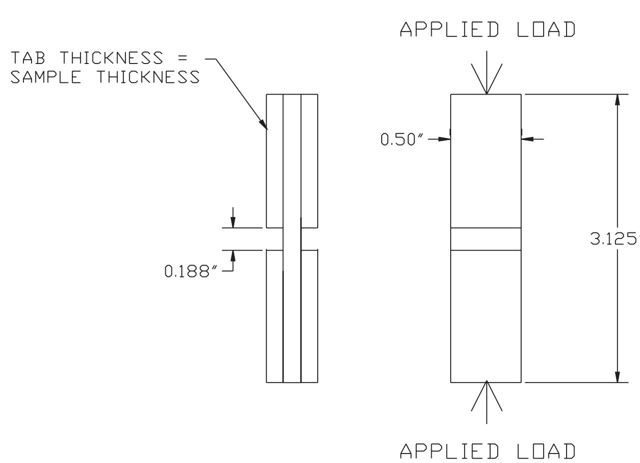


Figure 3-27 Test Specimen Configuration for SACMA SRM-1 Compression Test

Flexural Tests

For evaluation of mechanical properties of flat single-skin laminates under bending (flexural) loading, several standard procedures are available. The methods all involve application of a load which is out-of-plane, or normal to, the flat plane of the laminate. Properties obtained include flexural strength and flexural modulus.

Rectangular specimens are required regardless of reinforcement type. Unreinforced resin castings may also be tested using these procedures. Generally, a support span-to-sample depth ratio of between 14:1 and 20:1 is utilized (support span is 14-20 times the average laminate thickness). Load may be applied at the midpoint of the beam (3-point loading), or a 4-point loading scheme may be used. Flexural tests are excellent for comparing laminates of similar geometry and are often used in Quality Assurance programs.

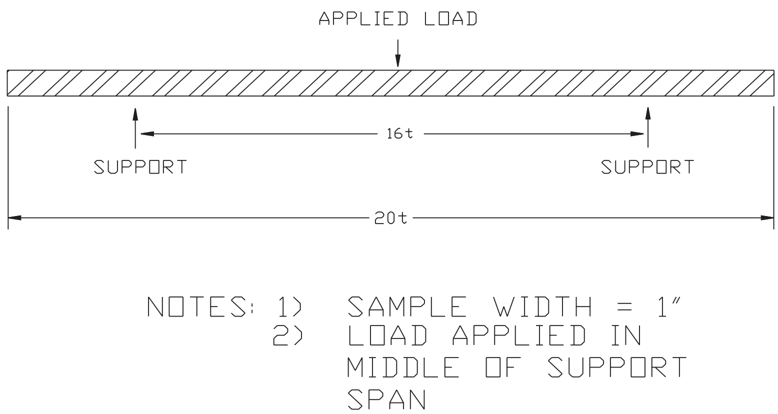


Figure 3-28 Test Specimen Configuration for ASTM D-790 Flexural Test, Method I, Procedure A

Flexural Test Methods	
ASTM D 790	Flexural Properties of Unreinforced and Reinforced Plastics and Electrical Insulating Materials Method I 3-point bending Method II 4-point bending
ISO 178	Plastics - Determination of Flexural Properties 3-point bending

Shear Tests

Many types of shear tests are available, depending on which plane of the single-skin laminate is to be subjected to the shear force. Various “in-plane” and “interlaminar” shear methods are commonly used. Confusion exists as to what properties are determined by the tests, however. The “short-beam” methods also are used to find “interlaminar” properties.

Through-plane shear tests are utilized for determination of out-of-plane shear properties, such as would be seen when drawing a screw or a bolt out of a panel. The load is applied perpendicular to, or “normal” to, the flat plane of the panel.

Properties obtained by these tests are shear strength, and in some cases, shear modulus.

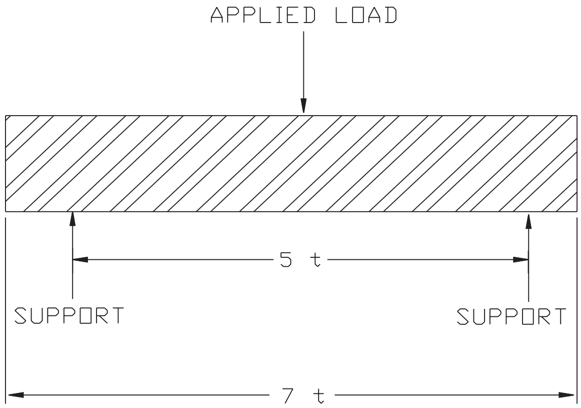


Figure 3-29 Test Specimen Configuration for ASTM D-2344 Short Beam Shear Test

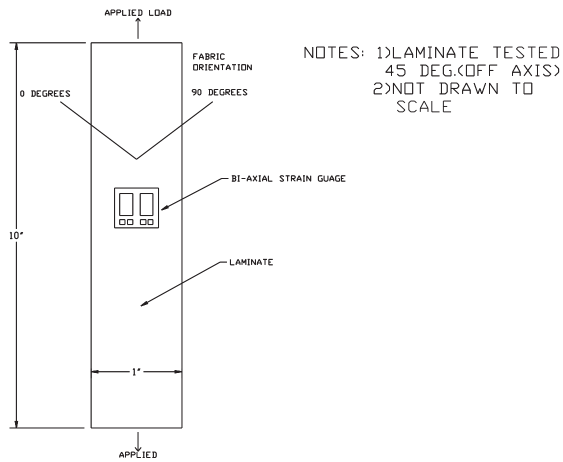


Figure 3-30 Test Specimen Configuration for ASTM D-3518 In-Plane Shear Test

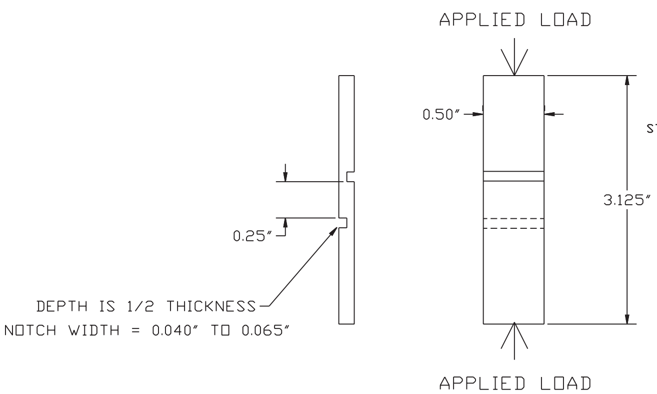


Figure 3-31 Test Specimen Configuration for ASTM D-3846 In-Plane Shear Test

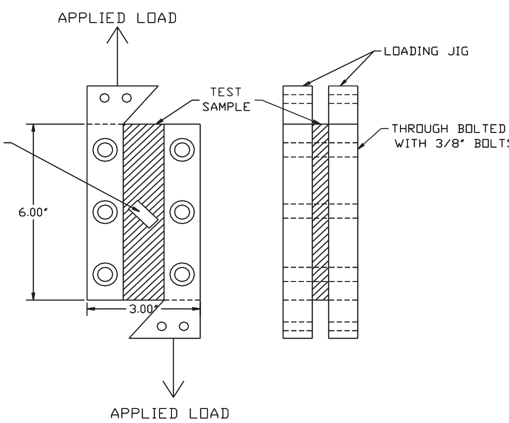


Figure 3-32 Test Specimen Configuration for ASTM D-4255 Rail Shear Test, Method A

Shear Test Methods	
ASTM D 3846	In-Plane Shear Strength of Reinforced Plastics
ASTM D 4255	Inplane Shear Properties of Composites Laminates
ASTM D 2344	Apparent Interlaminar Shear Strength of Parallel Fiber Composites by Short-Beam Method
ASTM D 3518	In-Plane Shear Stress-Strain Response of Unidirectional Polymer Matrix Composites
ASTM D 732	Shear Strength of Plastics by Punch Tool
ISO 4585	Textile Glass Reinforced Plastics - Determination of Apparent Interlaminar Shear Properties by Short-Beam Test
SACMA SRM 7	Inplane Shear Stress-Strain Properties of Oriented Fiber-Resin Composites
SACMA SRM 8	Short Beam Shear Strength of Oriented Fiber-Resin Composites

Impact Tests

Two basic types of impact tests are available for single-skin laminates. The “Izod” and “Charpy” tests utilize a pendulum apparatus, in which a swinging hammer or striker impacts a gripped rectangular specimen. The specimen may be notched or unnotched. Also, the specimen may be impacted from an edgewise face or a flatwise face.

Drop weight tests are performed by restraining the edges of a circular or rectangular specimen in a frame. A “tup” or impactor is dropped from a known height, striking the center of the specimen. The drop test is more commonly used for composite laminates

Impact Test Methods	
ASTM D 256	Impact Resistance of Plastics and Electrical Insulating Materials
ASTM D 3029	Impact Resistance of Flat, Rigid Plastic Specimens by Means of a Tup (Falling Weight)
ISO 179	Plastics - Determination of Charpy Impact Strength
ISO 180	Plastics - Determination of Izod Impact Strength

Resin/Reinforcement Content

The simplest method used to determine the resin content of a single-skin laminate is by a resin burnout method. The procedure is only applicable to laminates containing E-glass or S-glass reinforcement, however. A small specimen is placed in a pre-weighed ceramic crucible, then heated to a temperature where the organic resin decomposes and is burned off, leaving the glass reinforcement intact.

Laminates containing carbon or Kevlar® fibers cannot be analyzed in this way. As carbon and Kevlar® are also organic materials, they burn off together with the resin. More complicated resin “digestion” methods must be used. These methods attempt to chemically dissolve the resin with a strong acid or strong base. As the acid or base may also attack the reinforcing fibers, the accuracy of the results may be questionable if suitable precautions are not taken.

Fiber volume (%) may be calculated from the results of these tests if the dry density of the reinforcement is known.

Resin/Reinforcement Test Methods	
ASTM D 2584	Ignition Loss of Cured Reinforced Resins
ASTM D 3171	Fiber Content of Resin-Matrix Composites by Matrix Digestion
ISO 1172	Textile Glass Reinforced Plastics - Determination of Loss on Ignition

Hardness/Degree of Cure

The surface hardness of cured resin castings or reinforced plastics may be determined using “impressor” methods. A steel needle or cone is pushed into the surface and the depth of penetration is indicated on a dial gauge.

For cured polyester, vinyl ester, and DCPD type resins, the “Barcol” hardness is generally reported. Epoxy resins may be tested using either the “Barcol” or “Shore” type of test.

Hardness/Degree of Cure Test Methods	
ASTM D 2583	Indentation Hardness of Rigid Plastics by Means of a Barcol Impressor
ASTM D 2240	Rubber Property - Durometer Hardness

Water Absorption

Cured resin castings or laminates may be tested for resistance to water intrusion by simple immersion methods. A rectangular section is placed in a water bath for a specified length of time. The amount of water absorbed is calculated from the original and post-immersion weights. Tests may be performed at ambient or elevated water temperatures.

Water Absorption Test Methods	
ASTM D 570	Water Absorption of Plastics
ISO 62	Plastics - Determination of Water Absorption

Core Flatwise Tensile Tests

The tensile strength of a core material or sandwich structure may be evaluated using a “flatwise” test. Load is applied to the flat faces of a rectangular or circular specimen. This load is perpendicular to, or normal to, the flat plane of the panel.

Test specimens are bonded to steel blocks using a high strength adhesive. The assembly is then placed in a tensile holding fixture, through which load is applied to pull the blocks apart. Failures may be within the core material (cohesive), or between the core and FRP skin (adhesive), or a combination of both.

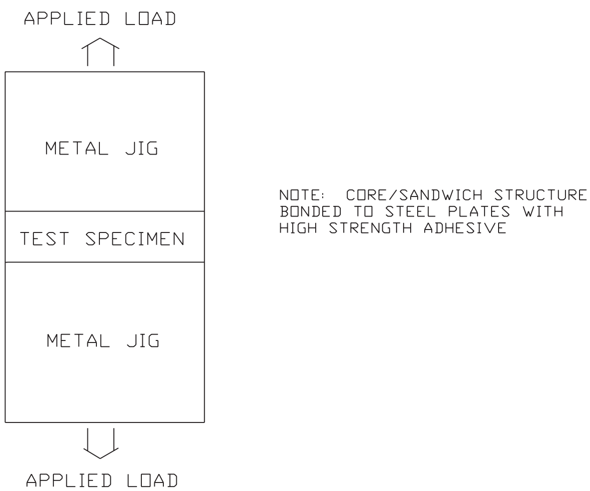


Figure 3-33 Test Specimen Configuration for ASTM C-297 Core Flatwise Tensile Test

Core Flatwise Tensile Test Methods	
ASTM C 297	Tensile Strength of Flat Sandwich Constructions in Flatwise Plane

Core Flatwise Compressive Tests

The compressive properties of core materials and sandwich structures are determined by loading the faces of flat, rectangular specimens. The specimen is crushed between two parallel steel surfaces or plates.

Typically, load is applied until a 10% deformation of the specimen has occurred (1.0" thick core compressed to 0.9", for example). The peak load recorded within this range is used to calculate compressive strength. Deformation data may be used for compressive modulus determination.

Core Flatwise Compressive Test Methods	
ASTM C 365	Flatwise Compressive Strength of Sandwich Cores
ASTM D 1621	Compressive Properties of Rigid Cellular Plastics

Sandwich Flexure Tests

The bending properties of sandwich panels can be evaluated using flexural methods similar to those utilized for single-skin laminates. A 3 or 4-point loading scheme may be used. Generally, the test is set up as a simply-supported beam, loaded at the midpoint (3-point). A 4-point setup can be selected if it is desired to produce higher shear stresses within the core.

Properties obtained from sandwich flexure tests include flexural modulus and panel stiffness, *EI*.

Sandwich Flexure Test Methods	
ASTM C 393	Flexural Properties of Flat Sandwich Constructions

Sandwich Shear Tests

The shear properties of sandwich panels and core materials are determined by a parallel plate test. Steel plates are bonded to the flat faces of rectangular sections. Load is applied to the plates so as to move them in opposing directions, causing shear stress in the specimen between the plates. Core shear strength is found from the load at failure. Shear modulus may be determined if plate-to-plate displacement is measured during the test.

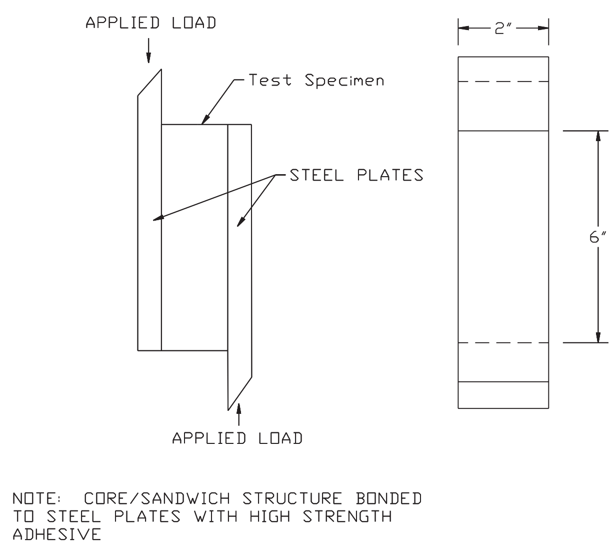


Figure 3-34 Test Specimen Configuration for ASTM C-273 Core Shear Test

Sandwich Shear Test Methods	
ASTM C 273	Shear Properties in Flatwise Plane of Flat Sandwich Constructions or Sandwich Cores

Peel Tests

The adherence of the FRP skins to a core in a sandwich structure may be evaluated using peel test methods. One FRP skin is restrained, while the opposite skin is loaded at an angle (starting at one edge of the specimen), to peel the skin away from the core. These methods may be utilized to determine optimum methods of bedding or adhesively bonding skins to sandwich cores.

Peel Test Methods	
ASTM D 1062 (modified)	Cleavage Strength of Metal-to-Metal Adhesive Bonds
ASTM D 1781	Climbing Drum Peel Test for Adhesives

Core Density

The density of core materials used in sandwich constructions is typically determined from a sample of raw material (unlaminated). A rectangular section is weighed, with the density calculated from the mass and volume of the specimen.

Core Density Test Methods	
ASTM D 1622	Apparent Density of Rigid Cellular Plastics
ASTM C 271	Density of Core Materials for Structural Sandwich Constructions

Machining of Test Specimens

A variety of tools are available which are suitable for cutting and machining of test specimens. These methods may be used for both single-skin laminates and sandwich structures. The tools normally utilized for specimen preparation include :

- Milling machine;
- Band saw;
- Wet saw, with abrasive blade (ceramic tile saw);
- Water jet cutter;
- Router, with abrasive bit; and
- Drum sander.

The wet cutting methods are preferred to reduce heating of the sample, and also reduce the amount of airborne dust generated. However, for necking down dumbbell specimens, a drum sander of the proper radius is often employed (with appropriate dust control).

Great care must be taken to assure that the specimens are cut in the correct orientation when directional fibers are present.

Machining Method	
ISO 2818	Plastics - Preparation of Test Specimens by Machining
ASTM D 4762	Testing Automotive/Industrial Composite Materials (Section 9 - Test Specimen Preparation)

Typical Laminate Test Data

Ideally, all testing should be conducted using standardized test methods. The standardized test procedures described above have been established by the American Society for Testing and Materials (ASTM, 100 Barr Harbor Drive, West Conshohocken, PA 19428-2959) and the Suppliers of Advanced Composite Materials Association (SACMA, 1600 Wilson Blvd., Suite 1008, Arlington, VA 22209). SACMA has developed a set of recommended test methods for oriented fiber resin composites. These tests are similar to ASTM standard tests, and are either improvements on the corresponding ASTM standard tests or are new tests to obtain data not covered by ASTM standard tests. The tests are intended for use with prepreg materials, thus some modifications may be necessary to accommodate common marine laminates. Also, the tolerances on fiber orientations (1°) and specimen size (approximately 0.005 inch) are not realistic for marine laminates. The individual tests have been established for specific purposes and applications. The tests may or may not be applicable to other applications and must be evaluated on a case by case basis.

There are three major types of testing: 1) tests of the FRP laminates, 2) tests of the individual FRP components, 3) tests of the FRP structure. In general, the tests of individual FRP components tend to be application dependent, however, some of the properties may not be useful in certain applications. Tests of the FRP laminates tend to be more application independent, and tests of FRP structures are heavily application dependent.

Appendix A contains test data on a variety of common marine reinforcements tested with ASTM methods by Art Wolfe at Structural Composites, Inc.; Dave Jones at Sigma; Tom Juska from the Navy's NSWC; and Rick Strand at Comtrex. In limited cases, data was supplied by material suppliers. Laminates were fabricated using a variety of resin systems and fabrication methods, although most were made using hand lay-up techniques. In general, test panels made on flat tables exhibit properties superior to as-built marine structures. Note that higher fiber content laminates will be thinner for the same amount of reinforcement used. This will result in higher mechanical values, which are reported as a function of cross sectional area. However, if the same amount of reinforcement is present in high- and low-fiber content laminates, they may both have the same "strength" in service. Indeed, the low-fiber content may have superior flexural strength as a result of increased thickness. Care must always be exercised in interpreting test data. Additionally, samples should be fabricated by the shop that will produce the final part and tested to verify minimum properties.

As can be seen in Appendix A, complete data sets are not available for most materials. Where available, data is presented for properties measured in 0°, 90° and ±45° directions. Shear data is not presented due to the wide variety in test methods used. Values for Poission's ratio are seldom reported. Lu and Jin reported on materials used for the construction of a 126 foot (38.5 meter) commercial fishing vessel built in China during the 1970's. [3-13] The mechanical data determined in their test program is presented here as typical of what can be expected using general purpose polyester resin and hand lay-up techniques.

Table 3-3 Ultimate Strengths and Elastic Constants for Polyester Resin Laminates [X.S. Lu & X.D. Jin, "*Structural Design and Tests of a Trial GRP Hull*," Marine Structures, Elsever, 1990]

	Test Angle	Quasi-Isotropic WR & Twill @ 0°/90°		Quasi-Isotropic WR & Twill @ 0°/90°/±45°		Unidirectional		Balanced WR & Twill @ 0°		Mostly WR & Twill @ 0°	
		ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa	ksi	MPa
Tensile Strength	0°	30.0	207	27.4	189	42.3	292	29.1	201	36.5	252
	90°	25.9	179	26.5	183	10.7	74	28.0	193	n/a	
	±45°	17.5	121	19.6	135	n/a		17.8	123	n/a	
Compress Strength	0°	21.2	146	20.1	139	n/a		23.9	165	21.6	149
	90°	17.8	123	20.3	140	n/a		21.6	149	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
Flexural Strength	0°	36.7	253	36.1	249	n/a		39.7	274	40.3	278
	90°	39.6	273	38.4	265	n/a		35.8	247	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
In-Plane Shear	0°	n/a		n/a		n/a		n/a		n/a	
	90°	10.4	72	11.4	79	n/a		10.7	74	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
Out-of-Plane Shear	0°	14.3	99	14.3	99	n/a		14.6	101	15.1	104
	90°	14.3	99	13.8	95	n/a		13.6	94	n/a	
	±45°	n/a		n/a		n/a		n/a		n/a	
		msi	GPa	msi	GPa	msi	GPa	msi	GPa	msi	GPa
Tensile Modulus	0°	2.22	15.3	1.94	13.4	3.06	21.1	2.26	15.6	2.29	15.8
	90°	2.19	15.1	1.85	12.8	1.35	9.3	2.14	14.8	n/a	
	±45°	1.07	7.4	1.38	9.5	n/a		1.01	7.0	n/a	
Shear Modulus	In-Plane	0.44	3.03	0.65	4.51	n/a		0.36	2.45	n/a	
Poisson's Ratio	0°	0.15		0.23		0.19		0.14		n/a	
	90°	0.13		0.22		0.12		0.12		n/a	
	±45°	0.62		0.50		n/a		0.60		n/a	

Material Testing Conclusions

In the previous text there is a review of ASTM and SACMA test procedures for determining physical and mechanical properties of various laminates. In order to properly design a boat or a ship, the designer must have accurate mechanical properties. The properties important to the designer are the tensile strength and modulus, the compressive strength and modulus, the shear strength and modulus, the interply shear strength, and the flexural strength and modulus.

The ASTM and SACMA tests are all uniaxial tests. There are some parts of a boat's structure that are loaded uniaxially, however, much of the structure, the hull, parts of the deck and bulkheads, etc., receive multiaxial loads. Multiaxial tests are difficult to conduct and typically are only done with panel "structures," (i.e. sandwich or stiffened panels).

The marine industry has yet to develop a set of tests which yield the right type of data for the marine designer. Once this has been accomplished and an industry wide set of accepted tests has been developed, then a comprehensive testing program, testing all the materials that are commonly used in the marine industry, would be very beneficial to the designers to try to yield some common data. Meanwhile, until these tests are developed, there is still a need for some common testing. In particular, the minimum tests recommended to be performed on laminates are the ASTM D3039 tensile test or the appropriate SACMA variation of that, SRM 4-88.

The ASTM compressive tests all leave something to be desired for marine laminates. However, the SACMA compression test looks like it might yield some useful uniaxial compressive load data for marine laminates, and therefore, at this time would probably be the recommended test for compression data. Flexural data should be determined using ASTM D790. This is a fairly good test.

As far as shear is concerned, there is really no good test for determining inplane shear properties. The ASTM test (D3518) is basically a 3039 tensile test performed on a fabric that has been laid up at a bias so that all the fibers are at ± 45°. This has a number of problems, since the fibers are not continuous, and the results are heavily dependent on the resin, much more so than would be in a continuous laminate. Some recent investigations at Structural Composites, Inc. has shown that wider samples with associated wider test grips will yield higher test values.

Therefore, there is currently not a test that would yield the right type of data for the inplane shear properties. For interply shear, about the only test that's available is the short beam shear test (ASTM D2344). The data yielded there is more useful in a quality control situation. It may be, however, that some of the other tests might yield some useful information. There's a shear test where slots are cut half way through the laminate on opposite sides of the laminate (ASTM D3846). This one might yield some useful information, but because the laminate is cut with the inherent variability involved, it difficult to come up with consistent data.

In summary, what is recommended as a comprehensive laminate test program is the ASTM D3039 tensile test, the SACMA compressive test, ASTM D790 flexural test and a panel test that realistically models the edge conditions. This type of test will be discussed further under "sandwich panel testing (page 177). A laminate test program should always address the task objectives, i.e. material screening, preliminary design, detail design and the specific project needs.

Macromechanics

The study of macromechanics as applied to marine composite structures includes analysis of beams, panels and structures. A beam, in its simplest form, consists of one or more laminates supported at each end resisting a load in the middle. The beam usually is longer than it is wide and characteristics are considered to be two dimensional. Much testing of composites is done with beams, which may or may not be representative of typical marine structures.

Analyzing panel structures more closely matches the real world environment. If we consider a portion hull bottom bounded by stiffeners and bulkheads, it is apparent that distinct end conditions exist at each of the panel's four edges. Static and most certainly dynamic response of that panel will not always behave like a beam that was used to generate test data. Unfortunately, testing of panels is expensive and not yet universally accepted, resulting in little comparative data. Geometries of panels, such as aspect ratio and stiffener arrangement, can be used in conjunction with two-dimensional test data to predict the response of panel structures. Reichard and Bertlesen have investigated panel test methods to measure panel response to out-of-plane loads. Preliminary results of those tests are presented at the end of the chapter.

Sandwich panel construction is an extremely efficient way to resist out-of-plane loads that are often dominant in marine structures. The behavior of core materials varies widely and is very much a function of load time history. Static governing equations are presented here. Through-thickness stress distribution diagrams serve as illustrations of sandwich panel response.

With larger composite structures, such as deckhouses, masts or rudders, global strength or stiffness characteristics may govern the design. Global characteristics are very much a function of geometry. As composite materials are molded to their final form, the designer must have the ability to specify curved corners and surfaces that minimize stress concentrations.

Not to be overlooked is the important subject of joints and details. Failures in composite vessels tend to occur at some detail design area. The reason for this is twofold. First, unintended stress concentrations tend to occur in detail areas. Secondly, fabrication quality control is more difficult in tight, detailed areas.

Beams

Although actual marine structures seldom resemble two-dimensional beams, it is instructive to define moments and deflections for some idealized load and end conditions of statically determinate beams. The generalized relationship of stress in a beam to applied moment is:

$$\sigma = \frac{Mc}{I} \tag{3-43}$$

where:

σ = stress in the beam

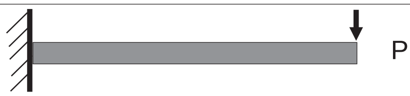
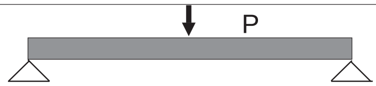
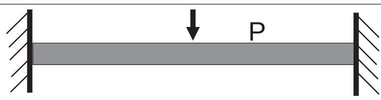
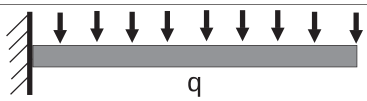
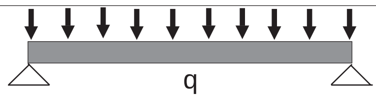
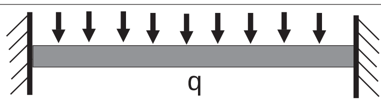
M = bending moment

c = vertical distance from the neutral axis

I = moment of inertia of the beam about the neutral axis

Expressions for moments and displacements for several types of beam loading scenarios are presented in Table 3-4.

Table 3-4 Maximum Moments and Deflections for Some Simple Beams

Load Cases	Maximum Moment	Maximum Deflection
	PL	$\frac{PL^3}{3EI}$
	$\frac{PL}{4}$	$\frac{PL^3}{48EI}$
	$\frac{PL}{8}$	$\frac{PL^3}{192EI}$
	$\frac{qL^2}{2}$	$\frac{qL^4}{8EI}$
	$\frac{qL^2}{8}$	$\frac{5qL^4}{384EI}$
	$\frac{qL^2}{12}$	$\frac{qL^4}{384EI}$

P = concentrated load
L = beam length
q = load per unit length
E = beam elastic modulus
I = beam moment of inertia

Panels

Throughout this discussion of marine panel structures, formulas will appear that have varying coefficients for “clamped,” “pinned,” and “free” end conditions. The end condition of a panel is the point where it attaches to either a bulkhead or a stiffener. With composite structures, the actual end condition is usually somewhere between “fixed” and “pinned,” depending upon the attachment detail. It is common practice for designers to perform calculations for both conditions and choose a solution somewhere in between the two. For truly “fixed” conditions, stress levels near the ends will be greater because of the resisting moment introduced here. For purely “pinned” conditions, deflections in the center of the panel will be greater.

Unstiffened, Single-Skin Panels

Buckling Strength of Flat Panels

The buckling strength of hull, deck and bulkhead panels is critical because buckling failure is often catastrophic, rather than gradual. The following discussion of flat panel buckling strength is contained in the Navy's DDS 9110-9 [3-14] and is derived from MIL-HDBK 17. [3-15]

The ultimate compressive stress, F_{ccr}, is given by the formula:

$$F_{ccr} = H_c \frac{\sqrt{E_{fa} E_{fb}}}{\lambda_{fba}} \left(\frac{t}{b}\right)^2 \tag{3-44}$$

where:

t = plate thickness

b = length of loaded edge

λ_{fba} = $1 - \mu_{fba}\, \mu_{fab}$

μ_{fba} = Poisson's ratio with primary stress in *b* direction

μ_{fab} = Poisson's ratio with primary stress in *a* direction

H_c = $h_c + C_c K_f$

h_c = coefficient from Figures 3-35 through 3-37

C_c = $\frac{\pi^2}{6}$ for edges simply supported or loaded edges clamped

= $\frac{2\,\pi^2}{9}$ for loaded edges simply supported, other edges clamped, or all edges clamped

K_f = $\dfrac{E_{fb}\, \mu_{fab} + 2\lambda_{fba}\, G_{ba}}{\sqrt{E_{fa}\, E_{fb}}}$

E_{fa} = flexural Young's modulus in *a* direction

E_{fb} = flexural Young's modulus in *b* direction

G_{ba} = shear modulus in the *ba* direction

The edge stiffener factor, *r*, is computed as follows:

$$r = \frac{a}{b} \left(\frac{E_{fb}}{E_{fa}}\right)^{\frac{1}{4}} \tag{3-45}$$

The ultimate shear stress due to buckling loads, F_{scr}, is given by the following formula:

$$F_{scr} = \frac{H_s \,(E_f^{\,3}\, E_{fa})^{\frac{1}{4}}}{3\,\lambda_{fba}} \left(\frac{t}{b}\right)^2 \tag{3-46}$$

where H_s is given in Figures 3-38 and 3-39 as a function of edge stiffener factor, *r*.

It should be noted that if "ultimate" stress levels are used for computational purposes, safety factors of 4.0 on compressive failures and 2.0 on shear failures are generally applied when developing scantlings for composite materials.

Panels Subject to Uniform, Out-of-Plane Loads

Out-of-plane loads, such as hydrostatic pressure, wind loads and green sea deck loads are of constant concern for marine structures. Hull plating, decks, deckhouse structure and bulkheads all must withstand out-of-plane loads. As with in-plane loads, clamped edge conditions produce maximum stresses at the edges and simply supported edges produce maximum stress at the center of a panel. In extreme loading conditions or with extremely flexible laminates, panels will deform such that it is entirely in a state of tension. This condition is called "membrane" tension (see page 211). For stiffer panels subject to static loads, classical plate deflection theory requires that combined flexural and tensile stresses provide the following margin of safety:

$$\frac{f_{fb}}{F_{fb}} + \frac{f_{tb}}{F_{tb}} \leq \frac{1}{SF} \tag{3-47}$$

where, for simply supported edges:

$$f_{fb} = K_8 \left[C_f \frac{E_{fba}}{\lambda_{fba}} \left(\frac{t}{b}\right)^2 \left(\frac{\delta}{t}\right) \right] \tag{3-48}$$

$$f_{tb} = K_8^2 \; 2.572 \left[\frac{E_{tb}}{\lambda_{fba}} \left(\frac{t}{b}\right)^2 \left(\frac{\delta}{t}\right)^2 \right] \tag{3-49}$$

for clamped edges:

$$f_{fb} = K_8 \left[C_f \frac{E_{fb}}{\lambda_{fba}} \left(\frac{t}{b}\right)^2 \left(\frac{\delta}{t}\right) \right] \tag{3-50}$$

$$f_{tb} = K_8^2 \; 2.488 \left[\frac{E_{tb}}{\lambda_{fba}} \left(\frac{t}{b}\right)^2 \left(\frac{\delta}{t}\right)^2 \right] \tag{3-51}$$

K_8 is given for panels with $\delta \leq 0.5t$ in Figure 3-40 as a function of the previously defined edge stiffener factor, r. Multiply δ by K_8 for these panels to get a more accurate deflection, δ. The coefficient C_f is given in Figures 3-41 through 3-43 as a function of m, which, for simply supported edges, is defined as:

$$m = 2.778 \left(\frac{E_{tb}}{E_{fb}}\right)^{\frac{1}{2}} \left(\frac{\delta}{t}\right) \tag{3-52}$$

for clamped edges:

$$m = 2.732 \left(\frac{E_{tb}}{E_{fb}} \right)^{\frac{1}{2}} \left(\frac{\delta}{t} \right) \qquad (3\text{-}53)$$

The ratio of the maximum deflection to the panel thickness, $\frac{\delta}{t}$, is found using Figures 3-44 and 3-45. In these Figures, the ratio $\frac{\Delta}{t}$ uses the maximum deflection assuming loads resisted by bending. This ratio is calculated as follows, for simply supported edges:

$$\frac{\Delta}{t} = \frac{5\,\lambda_{fba}\; p\, b^4}{32\, E_{fb}\; t^4} \qquad (3\text{-}54)$$

for clamped edges:

$$\frac{\Delta}{t} = \frac{\lambda_{fba}\; p\, b^4}{32\, E_{fb}\; t^4} \qquad (3\text{-}55)$$

where:

p = load per unit area

Figures 3-41 and 3-42 also require calculation of the coefficient C as follows:

$$C = \frac{E_{tb}}{E_{fb}} \qquad (3\text{-}56)$$

Sandwich Panels

This treatment on sandwich analysis is based on formulas presented in the U.S. Navy's Design Data Sheet DDS-9110-9, ***Strength of Glass Reinforced Plastic Structural Members, Part II - Sandwich Panels*** [3-14] and MIL-HDBK 23 - ***Structural Sandwich Composites*** [3-16]. In general, the formulas presented apply to sandwich laminates with bidirectional faces and cores such as balsa or foam. Panels with strongly orthotropic skins (unidirectional reinforcements) or honeycomb cores require detailed analysis developed for aerospace structures. The following notation is used for description of sandwich panel response to in-plane and out-of-plane loads:

A = cross sectional area of a sandwich panel; coefficient for sandwich panel formulas
a = length of one edge of rectangular panel; subscript for “a” direction
B = coefficient for sandwich panel formulas
b = length of one edge of rectangular panel; subscript for “b” direction
C = subscript for core of a sandwich panel
cr = subscript for critical condition of elastic buckling
c = subscript for compression; coefficient for edge conditions of sandwich panels
D = bending stiffness factor for flat panels
d = sandwich panel thickness
E = Young's modulus of elasticity

F	=	ultimate strength of a laminate or subscript for face
$F.S.$	=	factor of safety
f	=	induced stress; subscript for bending or flexural strength
G	=	shear modulus
H	=	extensional or in-plane stiffness
h	=	distance between facing centroids of a sandwich panel
I	=	moment of inertia of laminate cross section
K, K_m	=	coefficients for formulas
L	=	unsupported length of panel; core axis for defining sandwich panel core properties
M	=	bending moment
n	=	number of half-waves of a buckled panel
p	=	unit load
Q	=	coefficient for sandwich panel formulas
r	=	radius of gyration; stiffness factor for panels; subscript for reduced
R	=	coefficient for sandwich panel formulas
s	=	subscript for shear
T	=	core axis for defining sandwich core properties
t	=	subscript for tension; thickness of sandwich skins
U	=	shear stiffness factor
V	=	shearing force
W	=	weight; core axis for defining sandwich panel core properties
Z	=	section modulus
α, β, γ	=	coefficients for sandwich panel formulas
λ_{fba}	=	$1-\mu_{fba}\,\mu_{fab}$
μ	=	Poisson's ratio; Poisson's ratio for strain when stress is in the direction of the first subscript, with two subscripts denoting direction
δ, Δ	=	deflection of laminate or panel

Out-of-Plane Bending Stiffness

The general formula used to predict the bending stiffness per unit width, D, for a sandwich laminate is:

$$D = \frac{1}{\frac{E_{F1}t_{F1}}{\lambda_{F1}} + \frac{E_C t_C}{\lambda_C} + \frac{E_{F2}t_{F2}}{\lambda_{F2}}}\left[\frac{E_{F1}t_{F1}}{\lambda_{F1}}\left(\frac{E_{F2}t_{F2}}{\lambda_{F2}}\right)h^2 + \frac{E_{F1}t_{F1}}{\lambda_{F1}}\left(\frac{E_C t_C}{\lambda_C}\right)\left(\frac{t_{F1}+t_C}{2}\right)^2 + \frac{E_{F2}t_{F2}}{\lambda_{F2}}\left(\frac{E_C t_C}{\lambda_C}\right)\left(\frac{t_{F2}+t_C}{2}\right)^2\right] + \frac{1}{12}\left[\frac{E_{F1}t_{F1}^3}{\lambda_{F1}} + \frac{E_C t_C^3}{\lambda_C} + \frac{E_{F2}t_{F2}^3}{\lambda_{F2}}\right] \qquad (3\text{-}57)$$

The above equation applies to sandwich laminates where faces *1* and *2* may have different properties. Values for flexural and compressive stiffness are to be taken in the direction of interest, i.e. *a* or *b* direction (0° or 90°). When inner and outer skins are the same, the formula for bending stiffness, D, reduces to:

$$D = \frac{E_F t_F h^2}{2\lambda_F} + \frac{1}{12}\left(\frac{2E_F t_F^3}{\lambda_F} + \frac{E_C t_C^3}{\lambda_C}\right) \qquad (3\text{-}58)$$

The second term in the above equation represents the individual core and skin stiffness contribution without regard to the location of the skins relative to the neutral axis. This term is often neglected or incorporated using the factor K, derived from figure 3-46. The bending stiffness equation then reduces to:

$$D = K \frac{E_F t_F h^2}{2\lambda_F} \tag{3-59}$$

If the sandwich laminate has thin skins relative to the core thickness, the term K will approach unity. If the Poisson's ratio is the same for both the inner and outer skin, then $\lambda_{F1} = \lambda_{F2} = \lambda$ and (3-57) for different inner and outer skins reduces to:

$$D = \frac{E_{F1} t_{F1} E_{F2} t_{F2} h^2}{\left(E_{F1} t_{F1} + E_{F2} t_{F2}\right) \lambda_F} \tag{3-60}$$

and (3-59) for similar inner and outer skins reduces to:

$$D = \frac{E_F t_F h^2}{2\,\lambda_F} \tag{3-61}$$

In-Plane Stiffness

The in-plane stiffness per unit width of a sandwich laminate, H, is given by the following equation for laminates with different skins:

$$H = E_{F1} t_{F1} + E_{F2} t_{F2} + E_C t_C \tag{3-62}$$

and for laminates with similar inner and outer skins:

$$H = 2E_F t_F + E_C t_C \tag{3-63}$$

Shear Stiffness

The transverse shear stiffness of a sandwich laminate with relatively thin skins is dominated by the core, and therefore is approximated by the following equation:

$$U = \frac{h^2}{t_C} G_C \approx hG_C \tag{3-64}$$

In-Plane Compression

Sandwich panels subject to in-plane compression must first be evaluated to determine the critical compressive load per unit width N_{cr}, given by the theoretical formula based on Euler buckling:

$$N_{cr} = K \frac{\pi^2}{b^2} D \tag{3-65}$$

By substituting equation (3-60), equation (3-65) can be rewritten to show the critical skin flexural stress, $F_{Fcr_{1,2}}$, for different inner and outer skins, as follows:

$$F_{Fcr_{1,2}} = \pi^2 K \frac{E_{F1} t_{F1} E_{F2} t_{F2}}{\left(E_{F1} t_{F1} + E_{F2} t_{F2}\right)^2} \left(\frac{h}{b}\right)^2 \frac{E_{F1,2}}{\lambda_F} \tag{3-66}$$

and for similar inner and outer skins:

$$F_{Fcr} = \frac{\pi^2 K}{4}\left(\frac{h}{b}\right)^2 \frac{E_F}{\lambda_F} \qquad (3\text{-}67)$$

In equations (3-66) and (3-67), use $E_F = \sqrt{E_{Fa}E_{Fb}}$ for orthotropic skins and b is the length of the loaded edge of the panel. The coefficient, K, is given by the sum of $K_F + K_M$. K_F is based on skin stiffness and panel aspect ratio and K_M is based on sandwich bending and shear stiffness and panel aspect ratio. K_F is calculated by the following for different inner and outer skins:

$$K_F = \frac{\left(E_{F1}t_{F1}^3 + E_{F2}t_{F2}^3\right)\left(E_{F1}t_{F1} + E_{F2}t_{F2}\right)}{12\, E_{F1}t_{F1}E_{F2}t_{F2}h^2} K_{MO} \qquad (3\text{-}68)$$

and for similar inner and outer skins:

$$K_F = \frac{t_F^2}{3h^2} K_{MO} \qquad (3\text{-}69)$$

In equations (3-68) and (3-69), K_{MO} is found in Figure 3-47. $K_{MO} = K_M$ when $V = 0$ (ignoring shear force). For $\frac{a}{b}$ aspect ratios greater than 1.0, assume $K_F = 0$.

Figures 3-48 to 3-59 are provided for determining the coefficient, K_M. These figures are valid for sandwich laminates with isotropic skins where $\alpha = 1.0$; $\beta = 1.0$; and $\gamma = 0.375$; and orthotropic skins where $\alpha = 1.0$; $\beta = 0.6$; and $\gamma = 0.2$, with α, β, and γ defined as follows:

$$\alpha = \sqrt{\frac{E_b}{E_a}} \qquad (3\text{-}70)$$

$$\beta = \alpha\mu_{ab} + 2\gamma \qquad (3\text{-}71)$$

$$\gamma = \frac{G_{ba}}{\sqrt{E_a E_b}} \qquad (3\text{-}72)$$

The figures for K_M require computation of the parameter V, which is expressed as:

$$V = \frac{\pi^2 D}{b^2 U} \qquad (3\text{-}73)$$

Substituting values for bending stiffness, D, and shear stiffness, U, V for different inner and outer skins shear can be expressed as:

$$V = \frac{\pi^2\, t_C\, E_{F1}t_{F1}E_{F2}t_{F2}}{\lambda_F b^2 G_C\, \left(E_{F1}t_{F1} + E_{F2}t_{F2}\right)} \qquad (3\text{-}74)$$

and for similar inner and outer skins:

$$V = \frac{\pi^2 \; t_C E_F t_F}{2\lambda_F b^2 G_C} \tag{3-75}$$

Figures 3-48 through 3-59 each show cusped curves drawn as dashed lines, which represent buckling of the panel with *n* number of waves. Minimum values of the cusped curves for K_M, which should be used for the design equations, are shown for various values of *V*.

Face Wrinkling

Face wrinkling of sandwich laminates is extremely difficult to predict, due to uncertainties about the skin to core interface and the initial waviness of the skins. The face wrinkling stress, F_W, required to wrinkle the skins of a sandwich laminate, is given by the following approximate formula:

$$F_W = Q\left(\frac{E_F E_C G_C}{\lambda_F}\right)^{\frac{1}{3}} \tag{3-76}$$

Q is presented in Figure 3-60, when a value for deflection, δ, is known or assumed and *K* is computed as follows:

$$K = \frac{\delta E_F}{t_F F_C} \tag{3-77}$$

Face wrinkling is more of a problem with “aerospace” type laminates that have very thin skins. Impact and puncture requirements associated with marine laminates usually results in greater skin thicknesses. Minimum suggested skin thicknesses based on the design shear load per unit length, N_S, is given by the following equation for different inner and outer skins:

$$N_S = t_{F1}F_{F1} + t_{F2}F_{F2} \tag{3-78}$$

and for similar inner and outer skins:

$$t_F = \frac{N_S}{2F_F} \tag{3-79}$$

Equations (3-66) and (3-67) can be used to calculated critical shear buckling, using Figures 3-61 through 3-66 for coefficients K_M and K_{MO}.

Out-of-Plane Loading

Out-of-plane or normal uniform loading is common in marine structures in the form of hydrostatic forces or live deck loads. The following formulas apply to panels with “simply supported” edges. Actual marine panels will have some degree of fixicity at the edges, but probably shouldn't be modeled as “fixed.” Assumption of end conditions as “simply supported” will be conservative and it is left up to the designer to interpret results.

The following formulas assist the designer in determining required skin and core thicknesses and core shear stiffness to comply with allowable skin stress and panel deflection. Because the "simply supported" condition is presented, maximum skin stresses occur at the center of the panel (*x*-*y* plane). Imposing a clamped edge condition would indeed produce a bending moment distribution that may result in maximum skin stresses closer to the panel edge.

The average skin stress, taken at the centriod of the skin, for different inner and outer skins is given by:

$$F_{F1,2} = K_2 \frac{pb^2}{ht_{F1,2}} \tag{3-80}$$

and for similar inner and outer skins:

$$F_F = K_2 \frac{pb^2}{ht_F} \tag{3-81}$$

with K_2 given in Figure 3-68.

The deflection, δ, is given by the following formulas for different inner and outer skins as:

$$\delta = \frac{K_1}{K_2}\left(\frac{F_{F1,2}}{E_{F1,2}}\right)\left(1 + \frac{E_{F1,2}t_{F1,2}}{E_{F2,1}t_{F2,1}}\right)\frac{b^2}{h} \tag{3-82}$$

and for similar inner and outer skins:

$$\delta = 2\frac{K_1}{K_2}\left(\frac{\lambda F_F}{E_f}\right)\left(\frac{b^2}{h}\right) \tag{3-83}$$

K_1 is given in Figure 3-67. The above equations need to be solved in an iterative fashion to ensure that both stress and deflection design constraints are satisfied. Additionally, core shear stress, F_{Cs}, can be computed as follows, with K_3 taken from Figure 3-69:

$$F_{Cs} = K_3\, p\, \frac{b}{h} \tag{3-84}$$

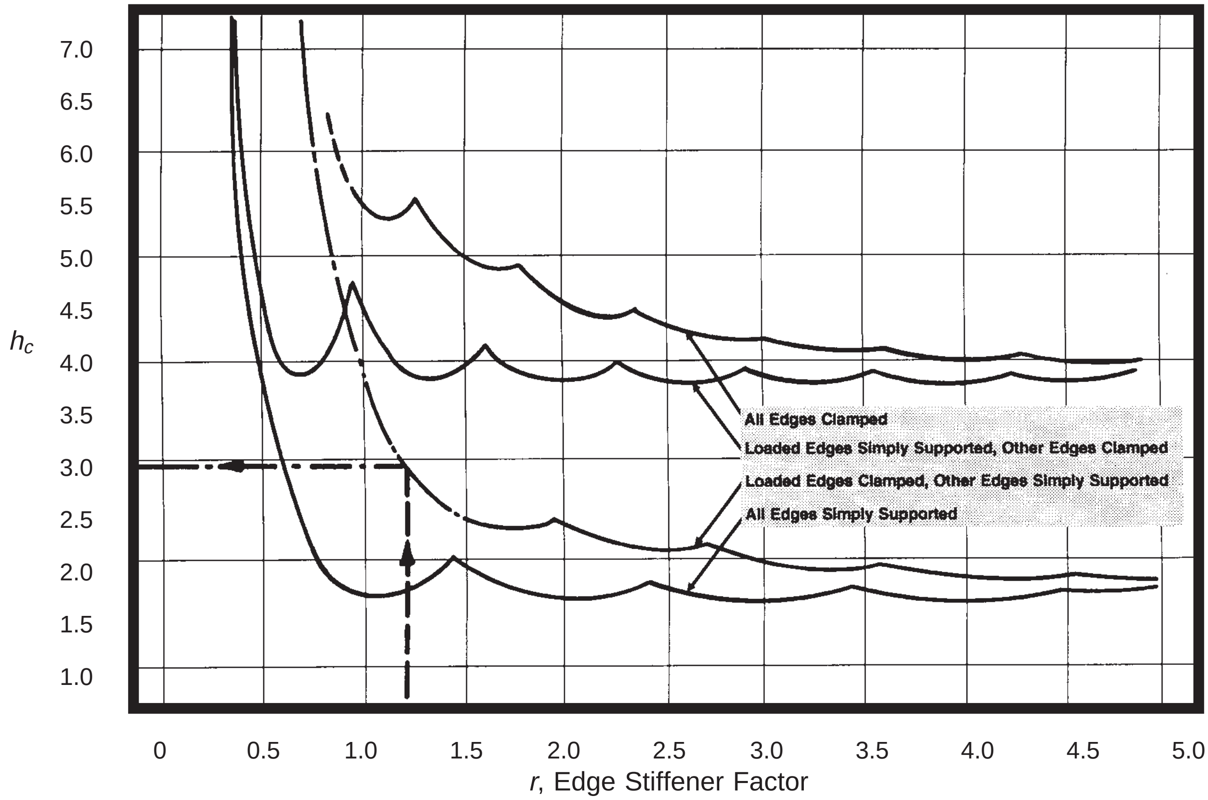


Figure 3-35 h_c as a Function of Edge Stiffener Factor [DDS 9110-9]

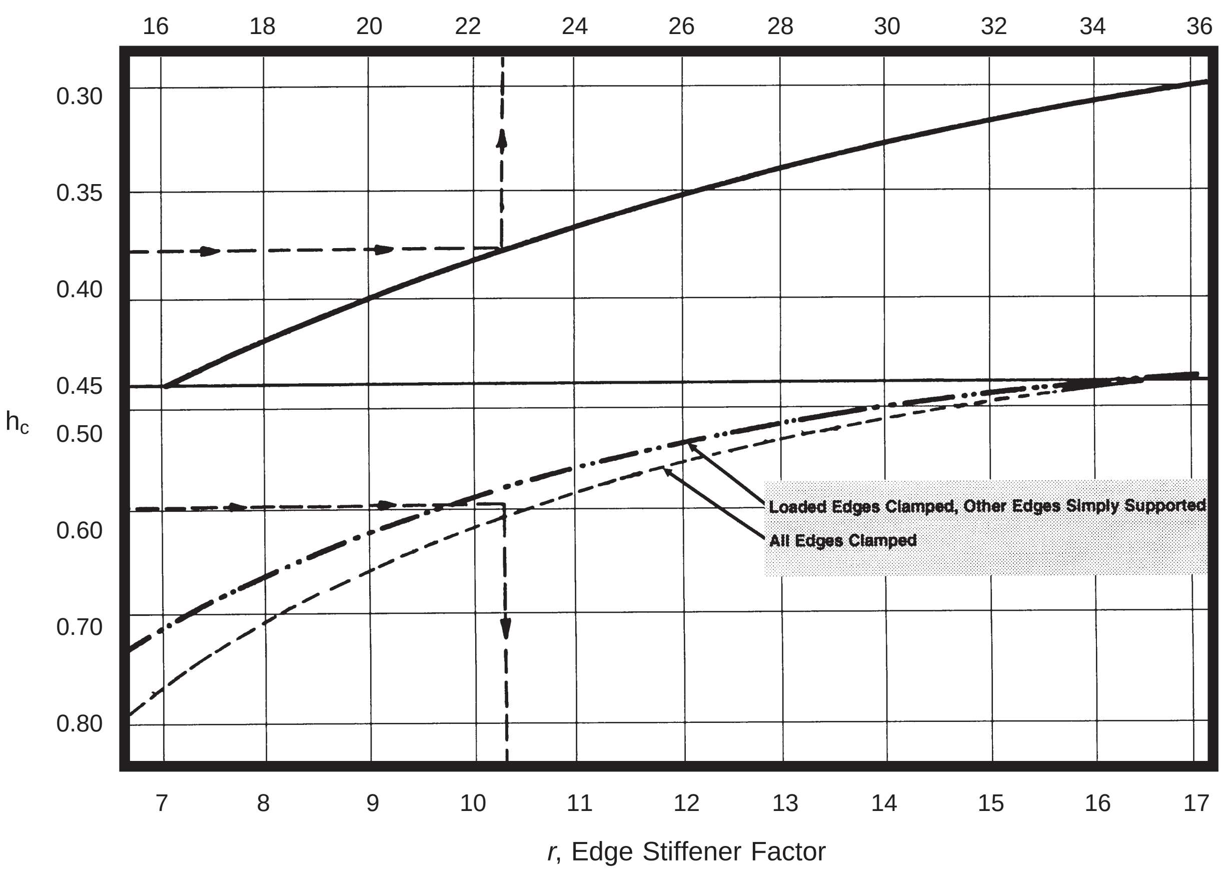


Figure 3-36 h_c as a Function of Edge Stiffener Factor [DDS 9110-9]

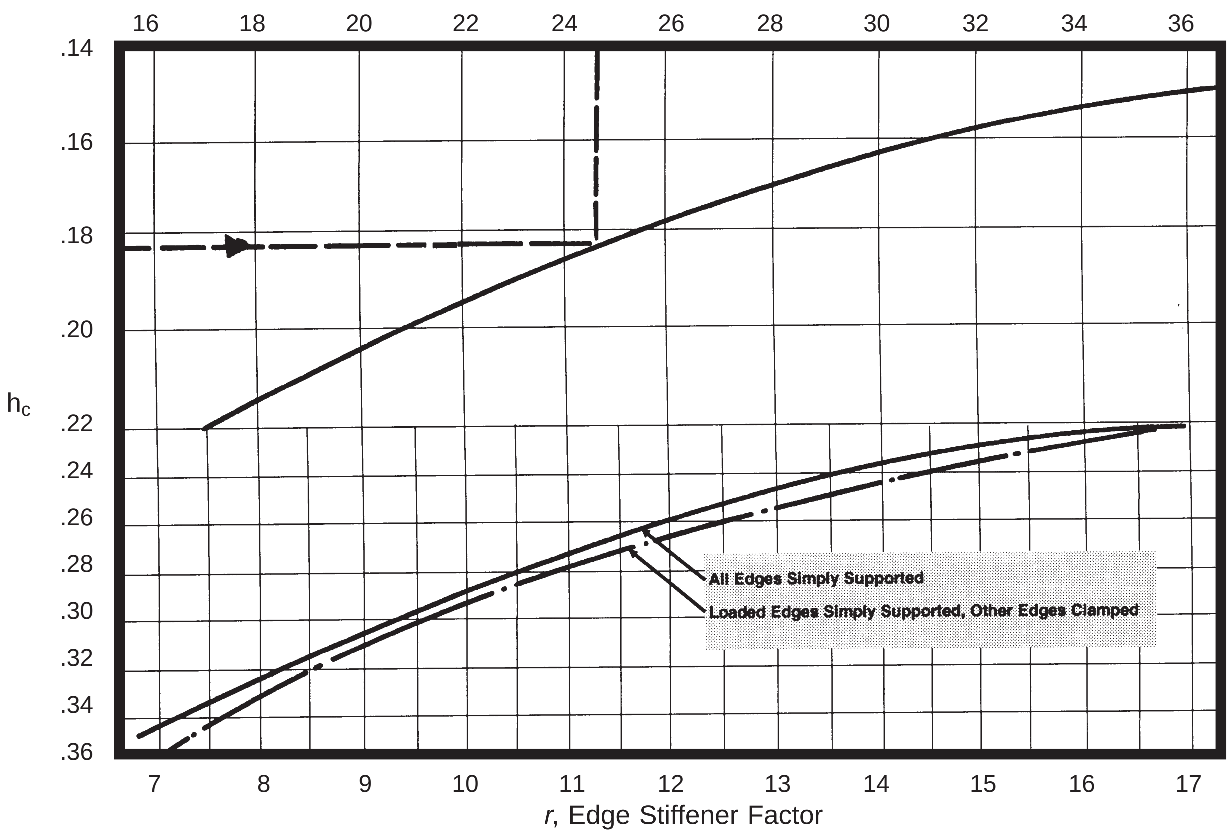


Figure 3-37 h_c as a Function of Edge Stiffener Factor [DDS 9110-9]

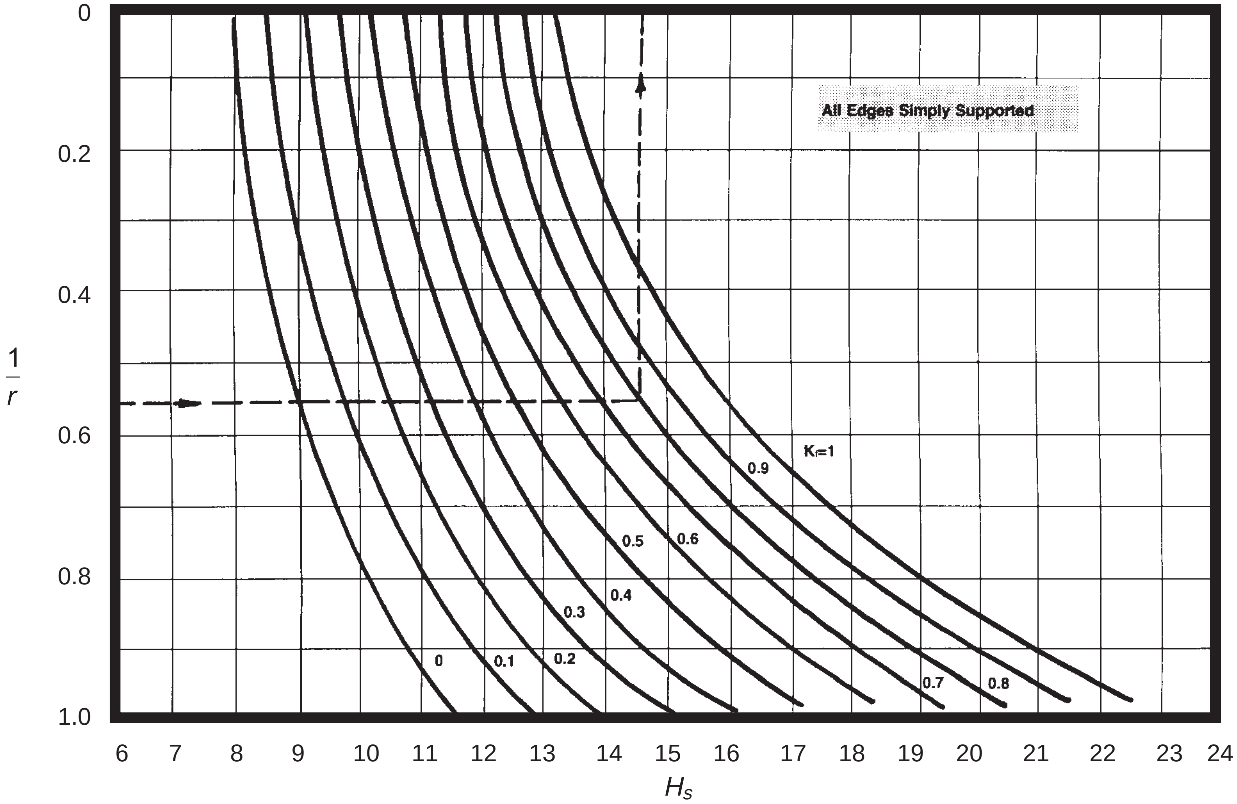


Figure 3-38 H_S as a Function of the Inverse of Edge Stiffener Factor [DDS 9110-9]

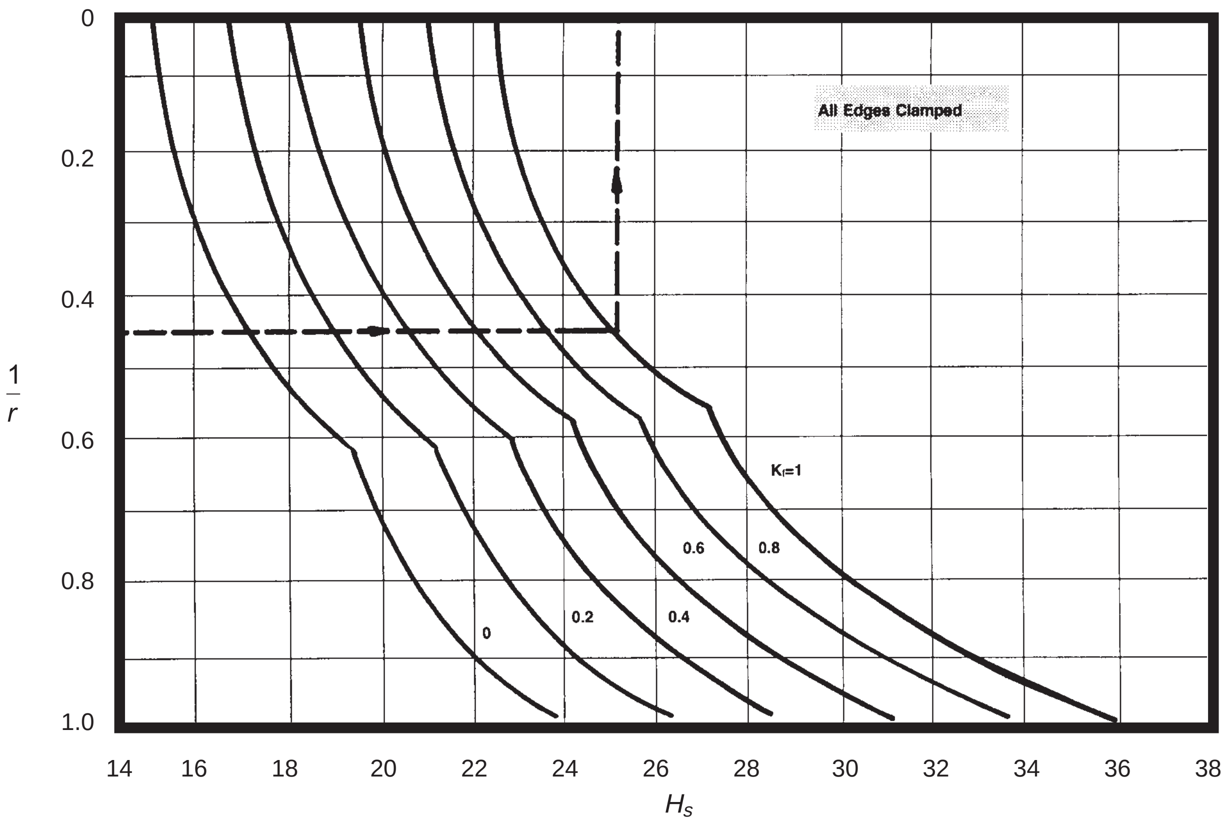


Figure 3-39 H_S as a Function of the Inverse of Edge Stiffener Factor [DDS 9110-9]

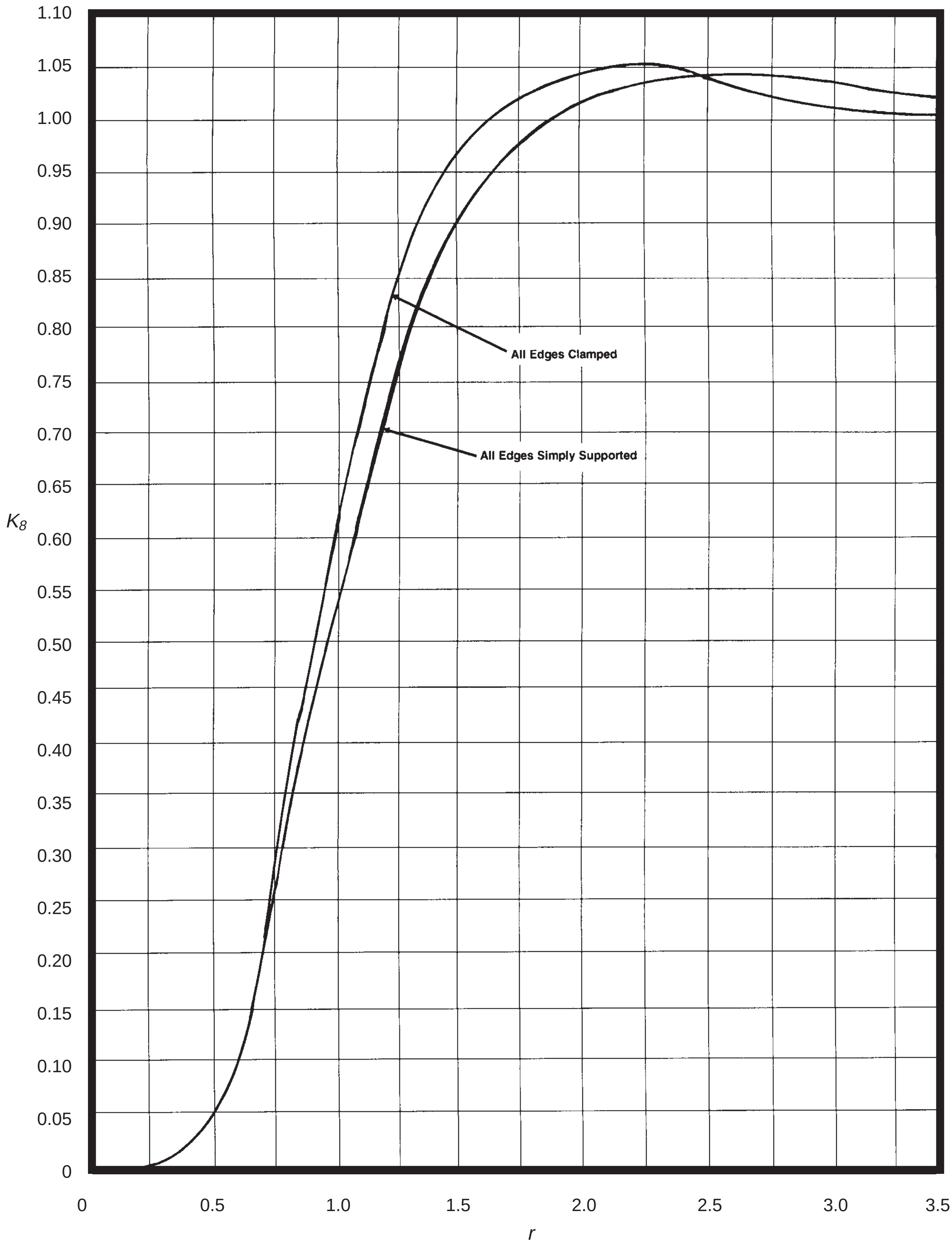


Figure 3-40 K_8 as a Function of Edge Stiffener Factor [DDS 9110-9]

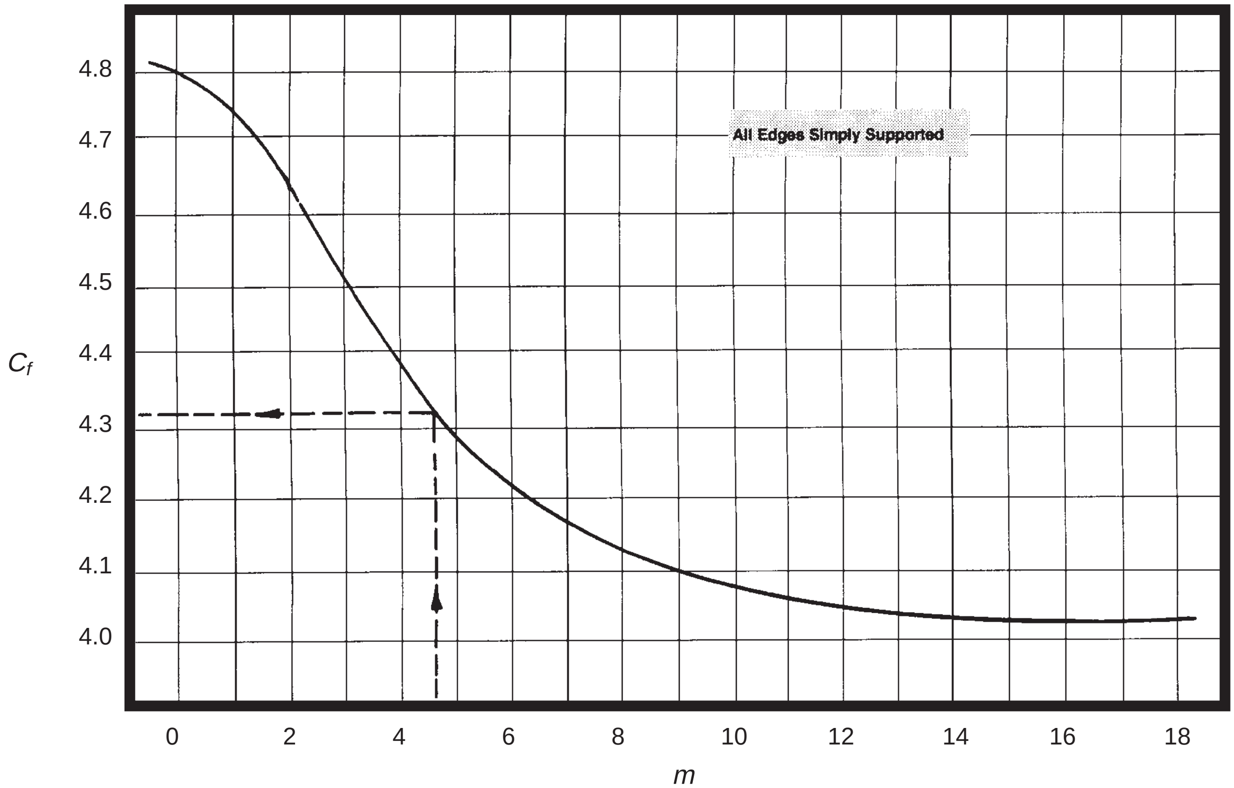


Figure 3-41 C_f as a Function of m [DDS 9110-9]

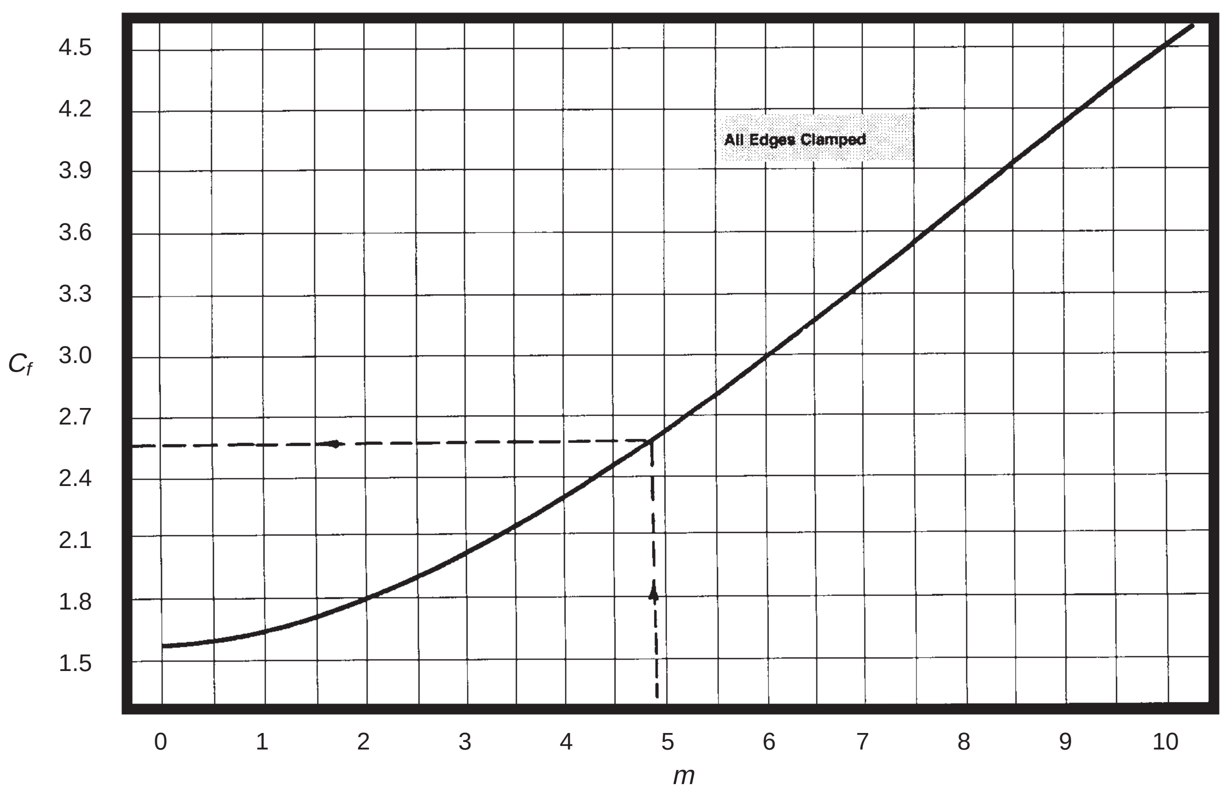


Figure 3-42 C_f as a Function of m [DDS 9110-9]

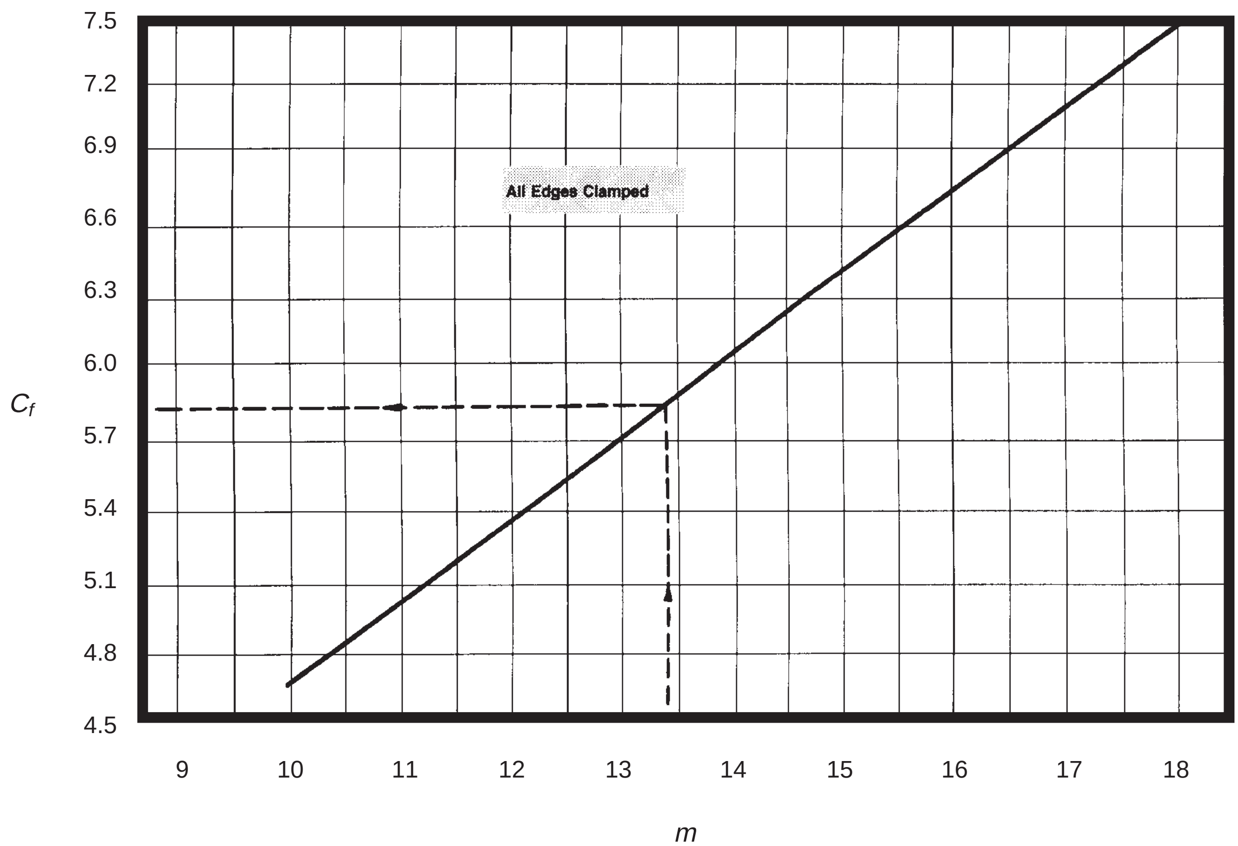


Figure 3-43 C_f as a Function of *m* [DDS 9110-9]

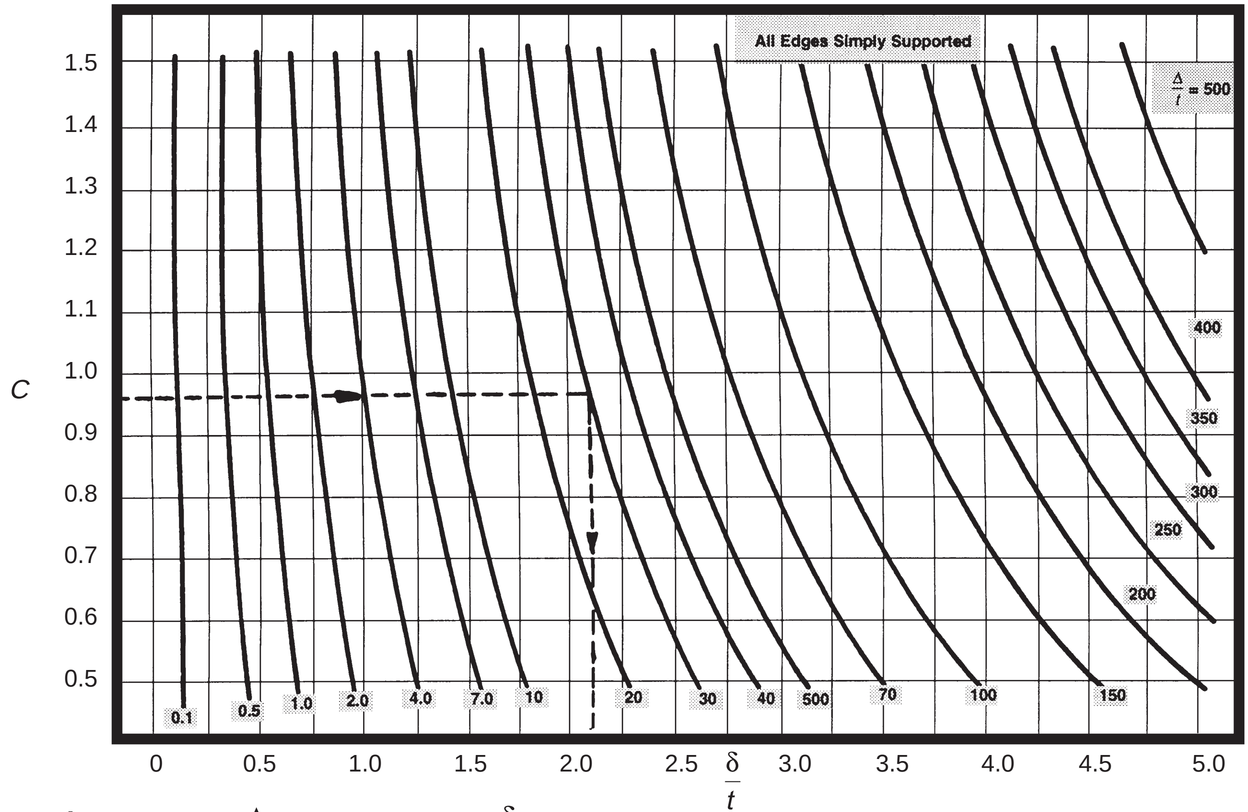


Figure 3-44 $\frac{\Delta}{t}$ as a Function of $\frac{\delta}{t}$ and C [DDS 9110-9]

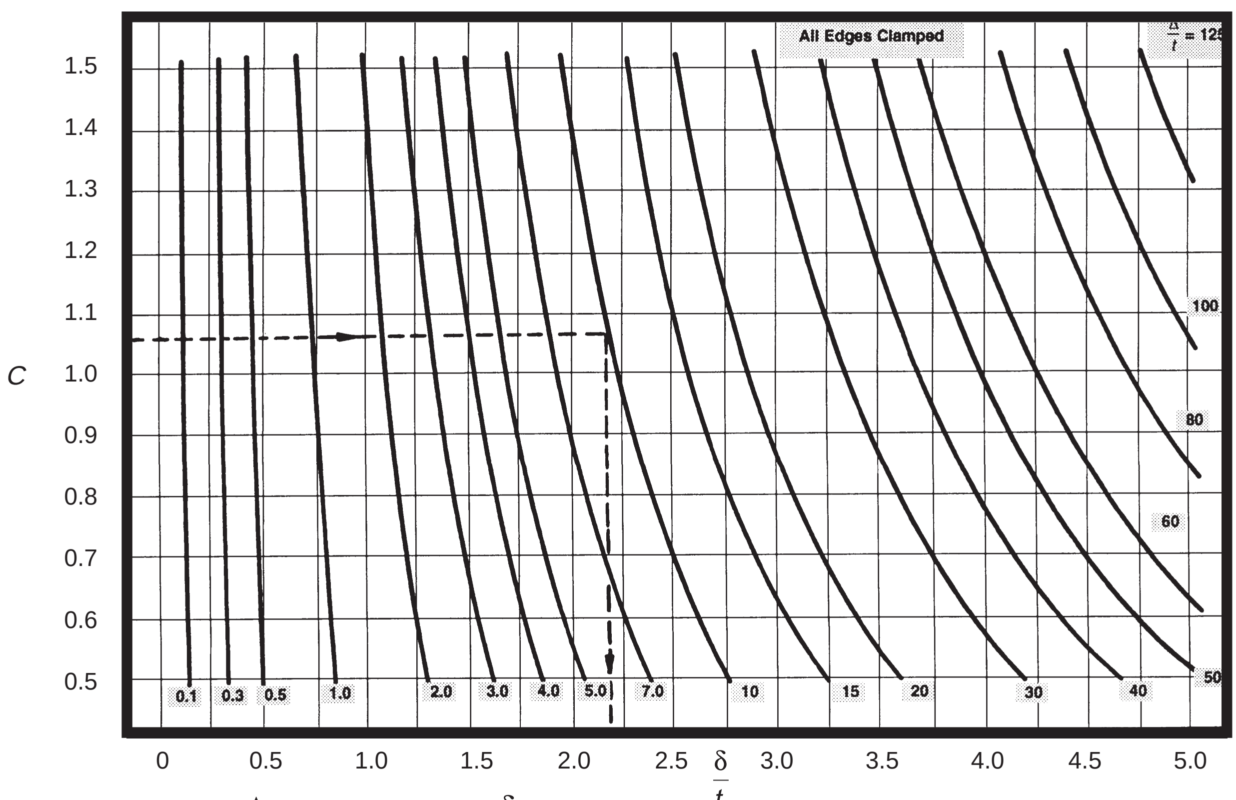


Figure 3-45 $\frac{\Delta}{t}$ as a Function of $\frac{\delta}{t}$ and C [DDS 9110-9]

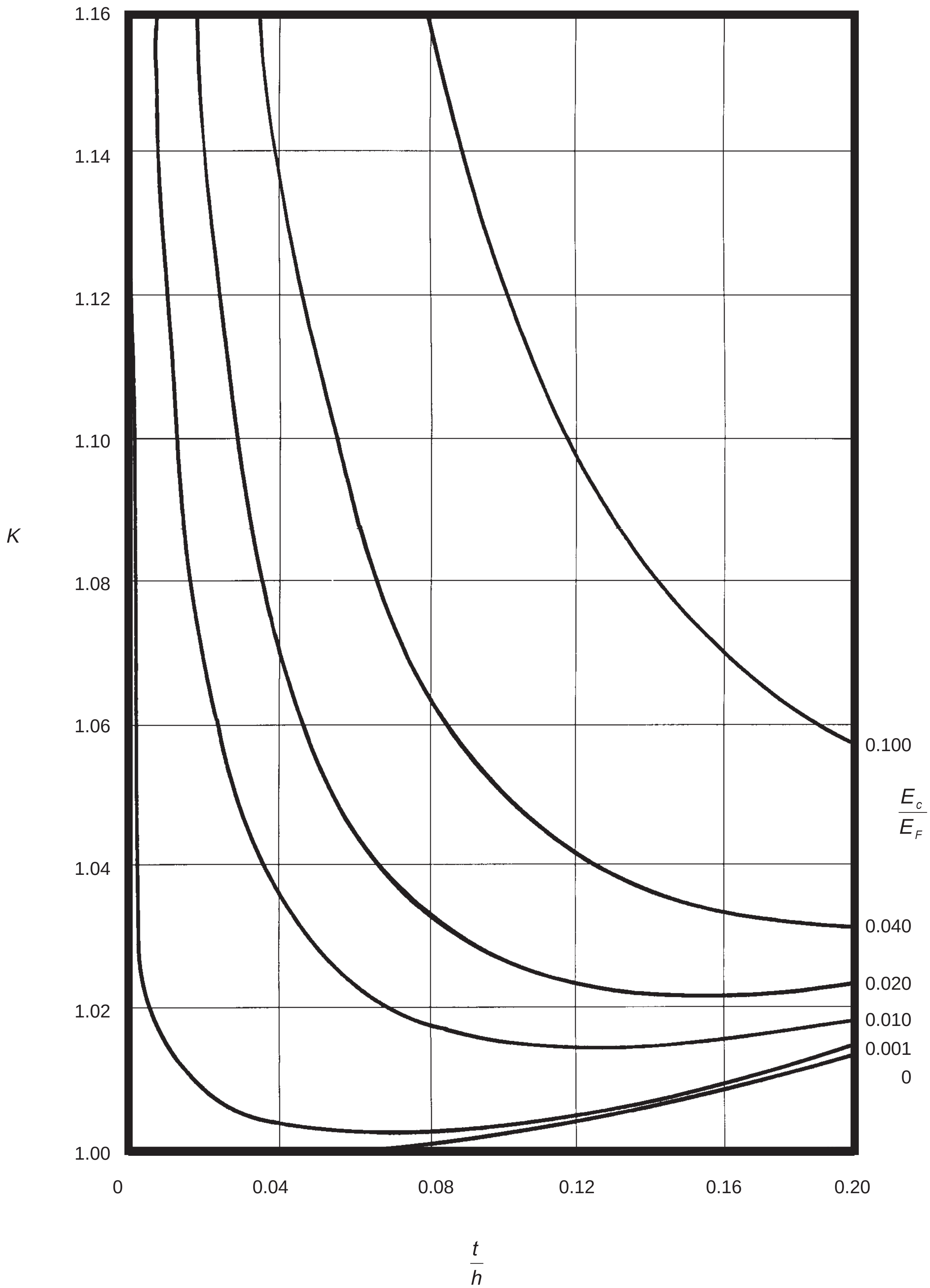


Figure 3-46 Coefficient for Bending Stiffness Factor [DDS 9110-9]

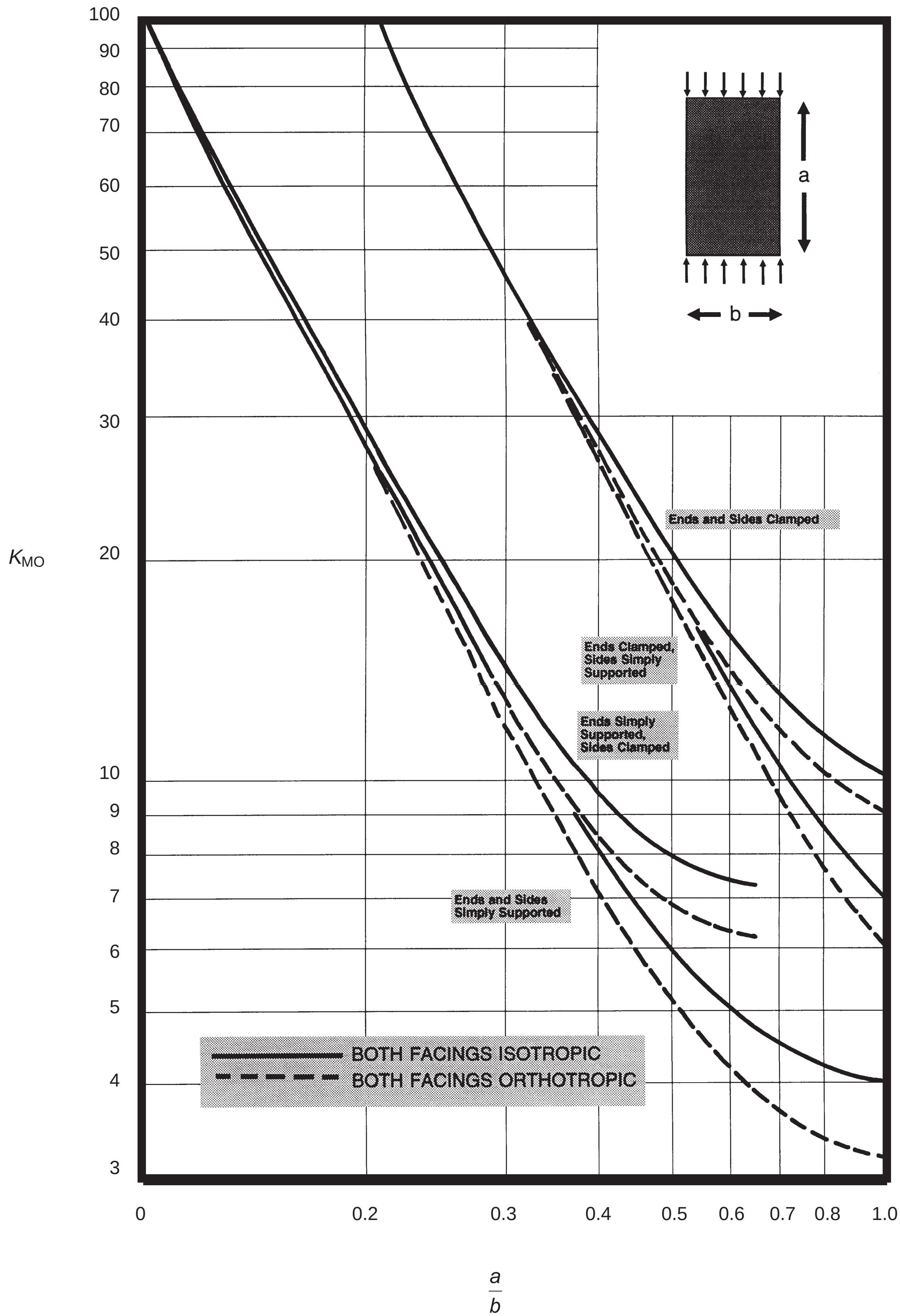


Figure 3-47 Values of K_{MO} for Sandwich Panels in Edgewise Compression [DDS 9110-9]

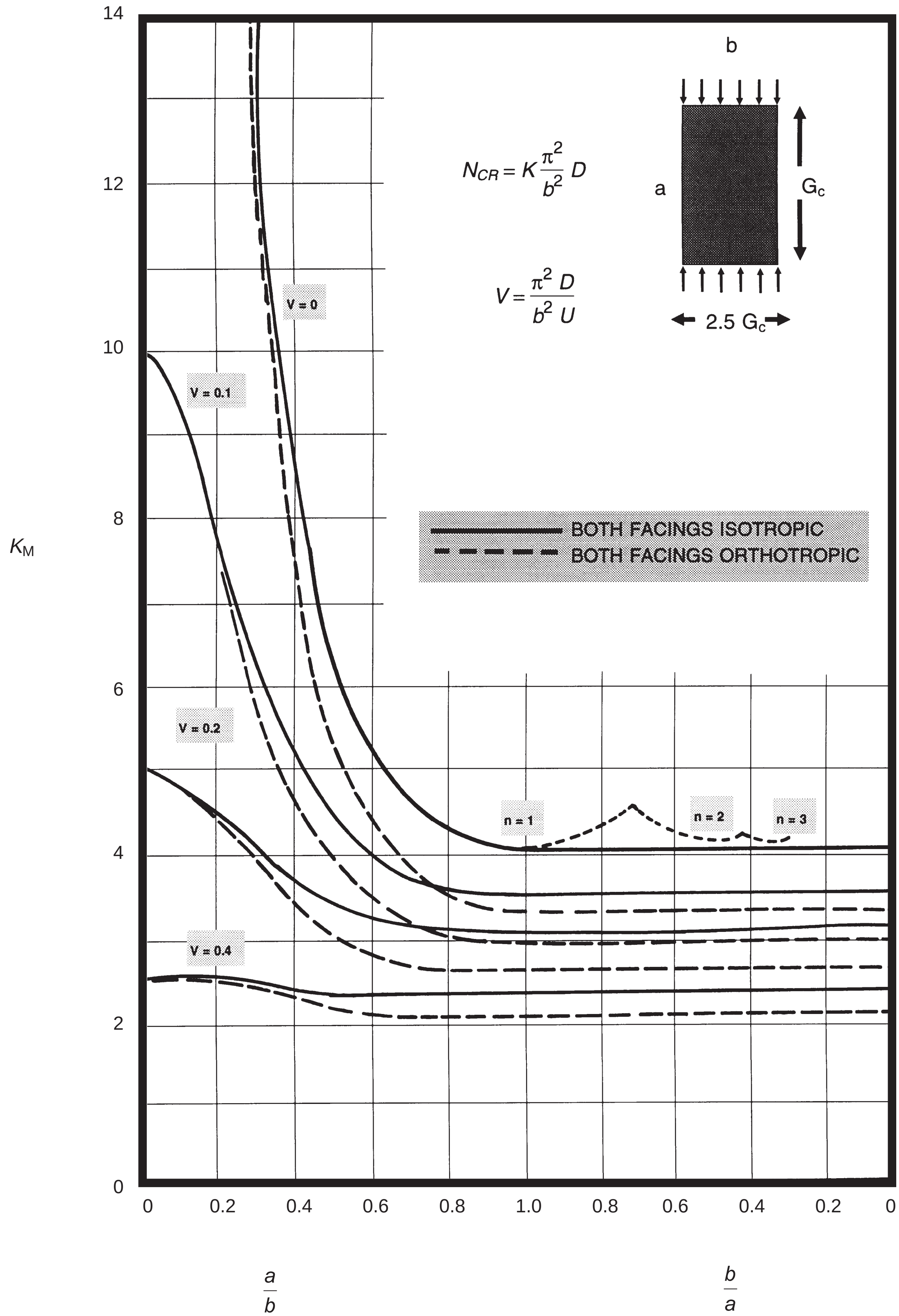


Figure 3-48 K_M for Sandwich Panels with Ends and Sides Simply Supported and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

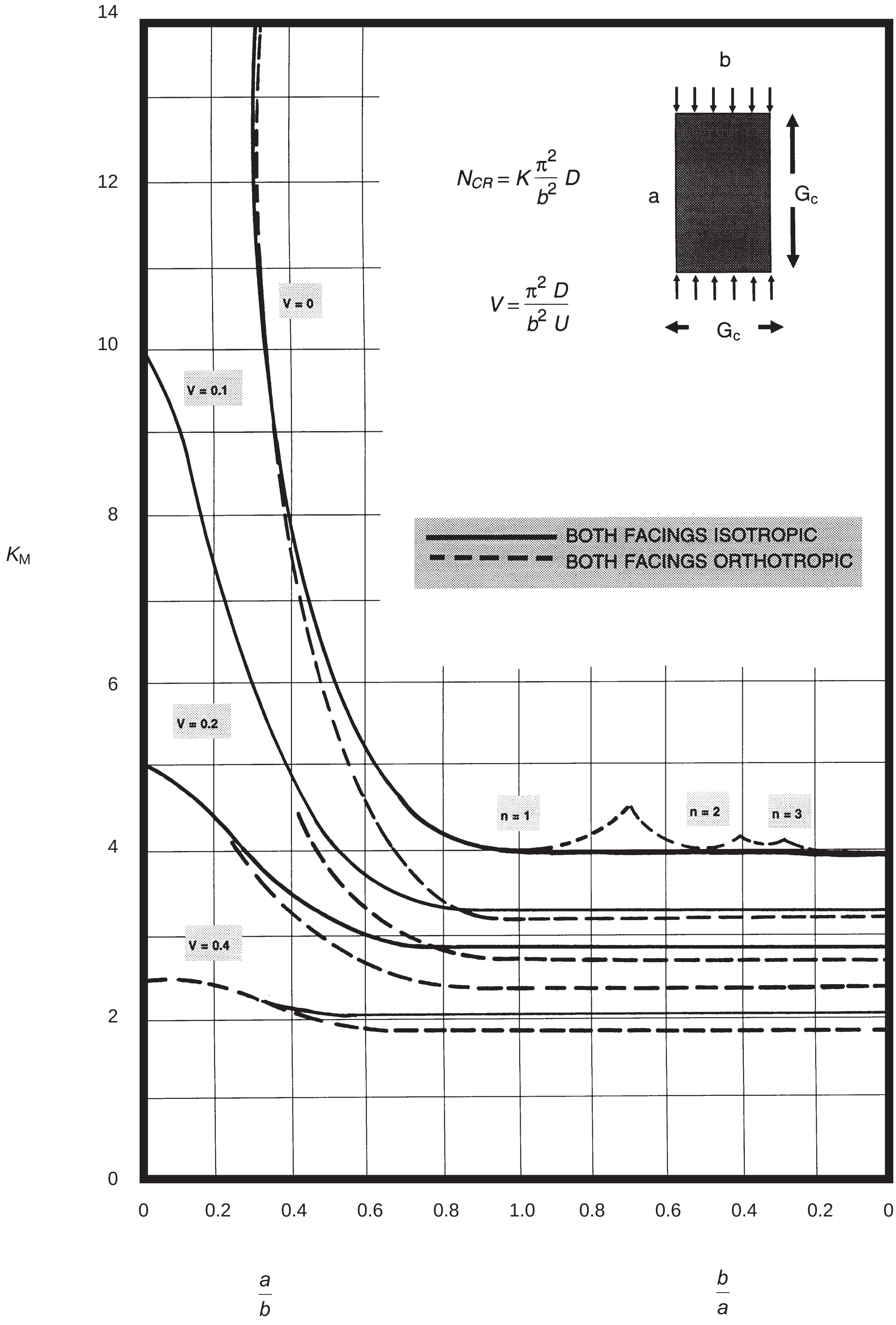


Figure 3-49 K_M for Sandwich Panels with Ends and Sides Simply Supported and Isotropic Core ($G_{Cb} = G_{Ca}$) [DDS 9110-9]

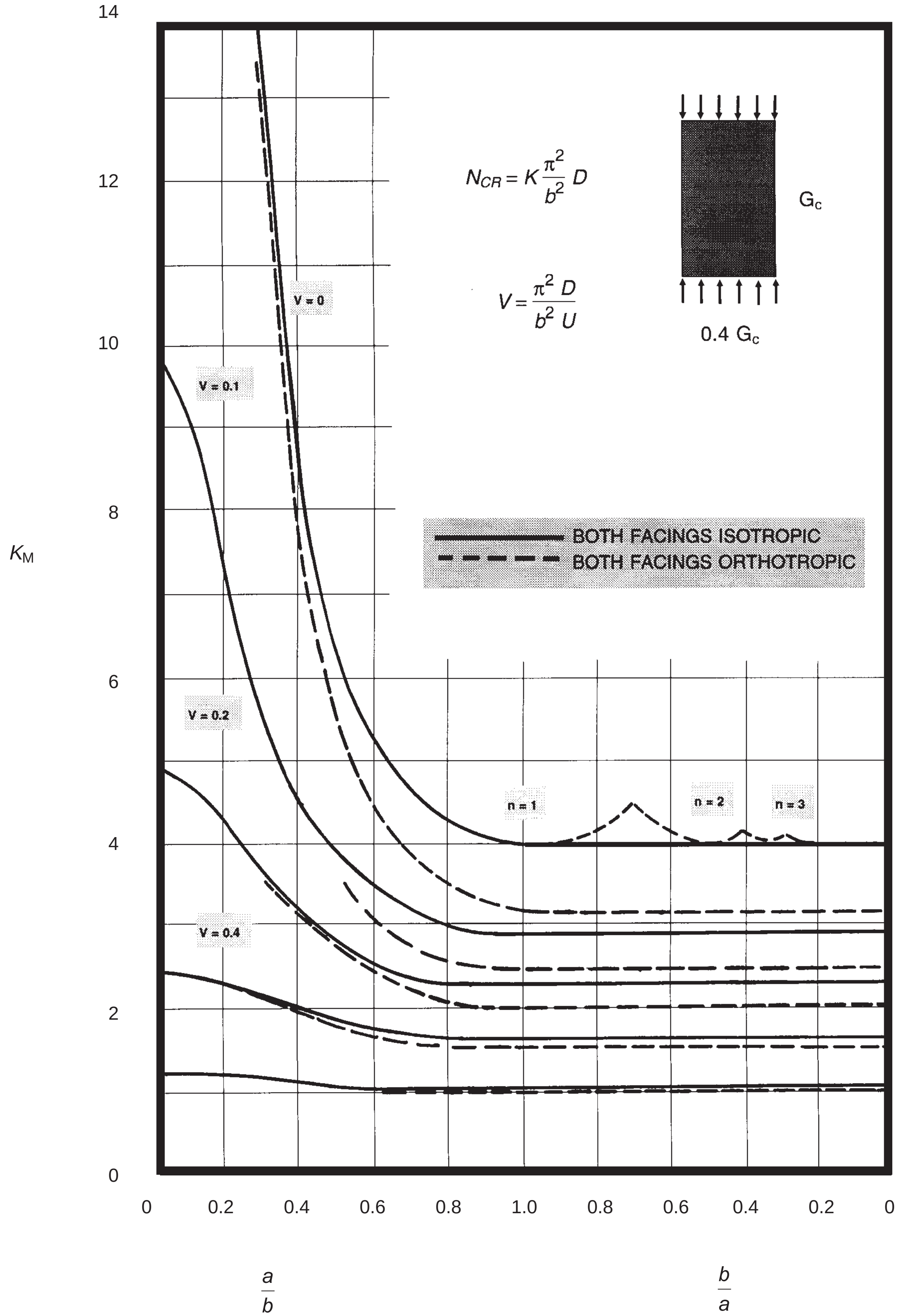


Figure 3-50 K_M for Sandwich Panels with Ends and Sides Simply Supported and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

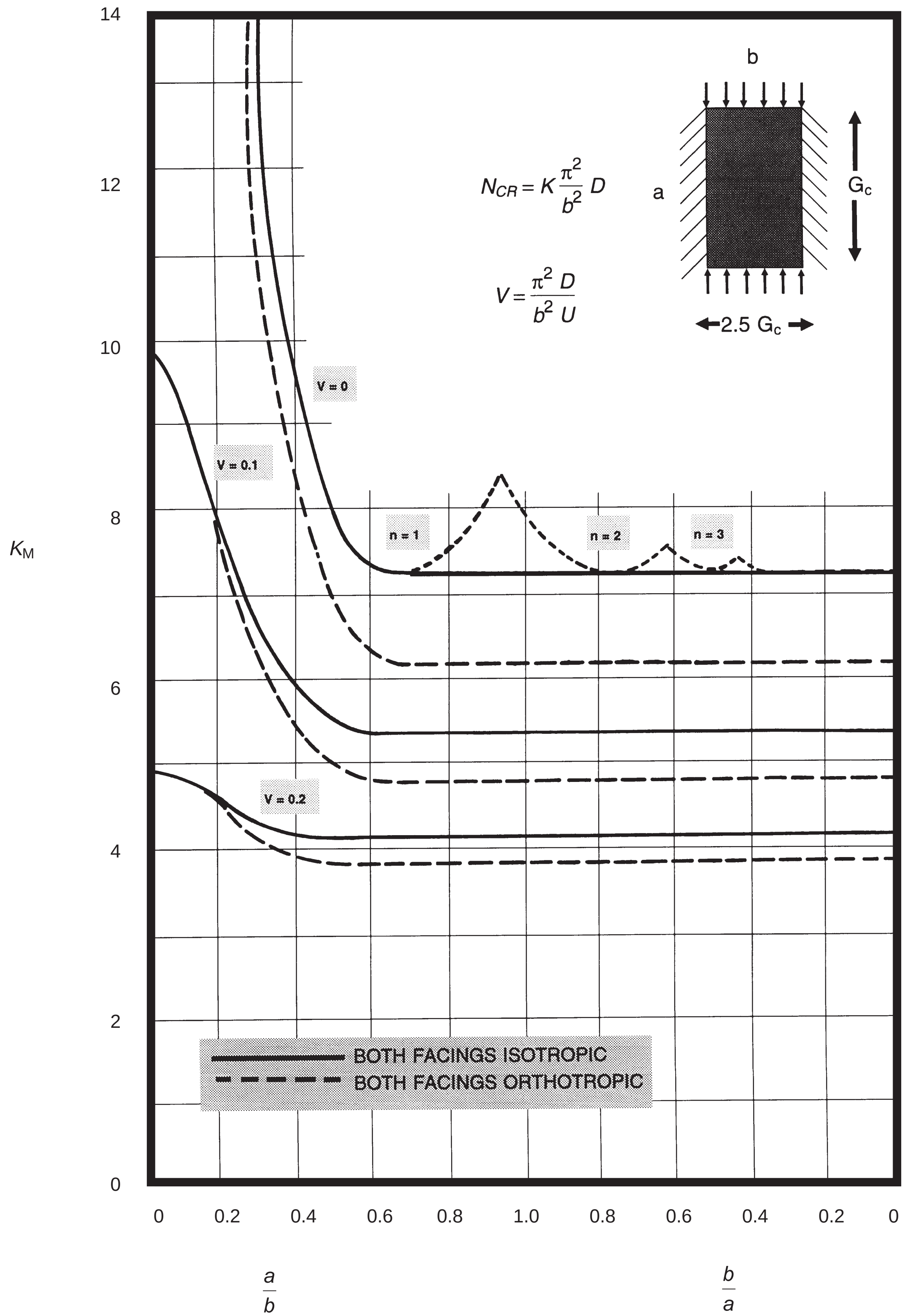


Figure 3-51 K_M for Sandwich Panels with Ends Simply Supported, Sides Clamped and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

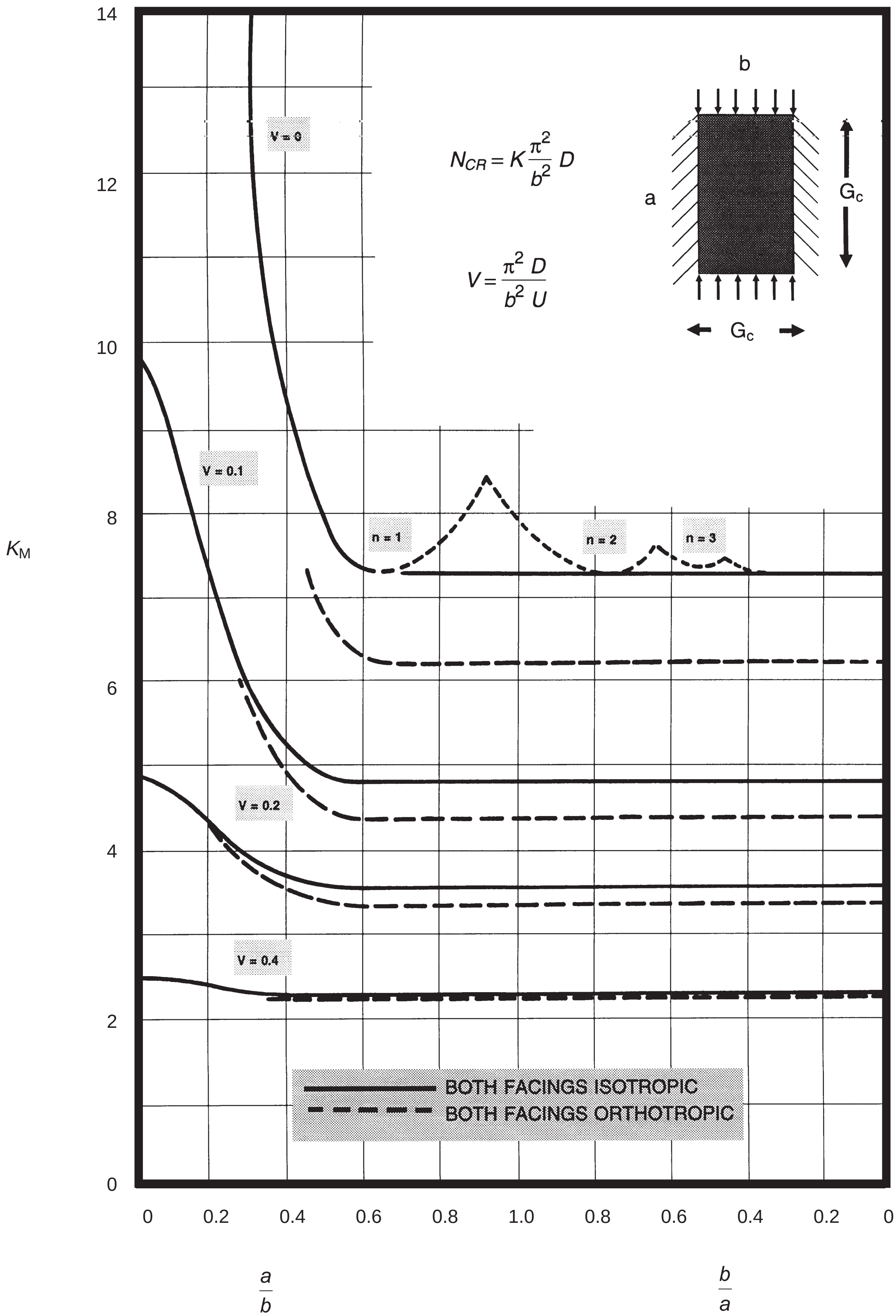


Figure 3-52 K_M for Sandwich Panels with Ends Simply Supported, Sides Clamped and Isotropic Core ($G_{Cb} = G_{Ca}$) [DDS 9110-9]

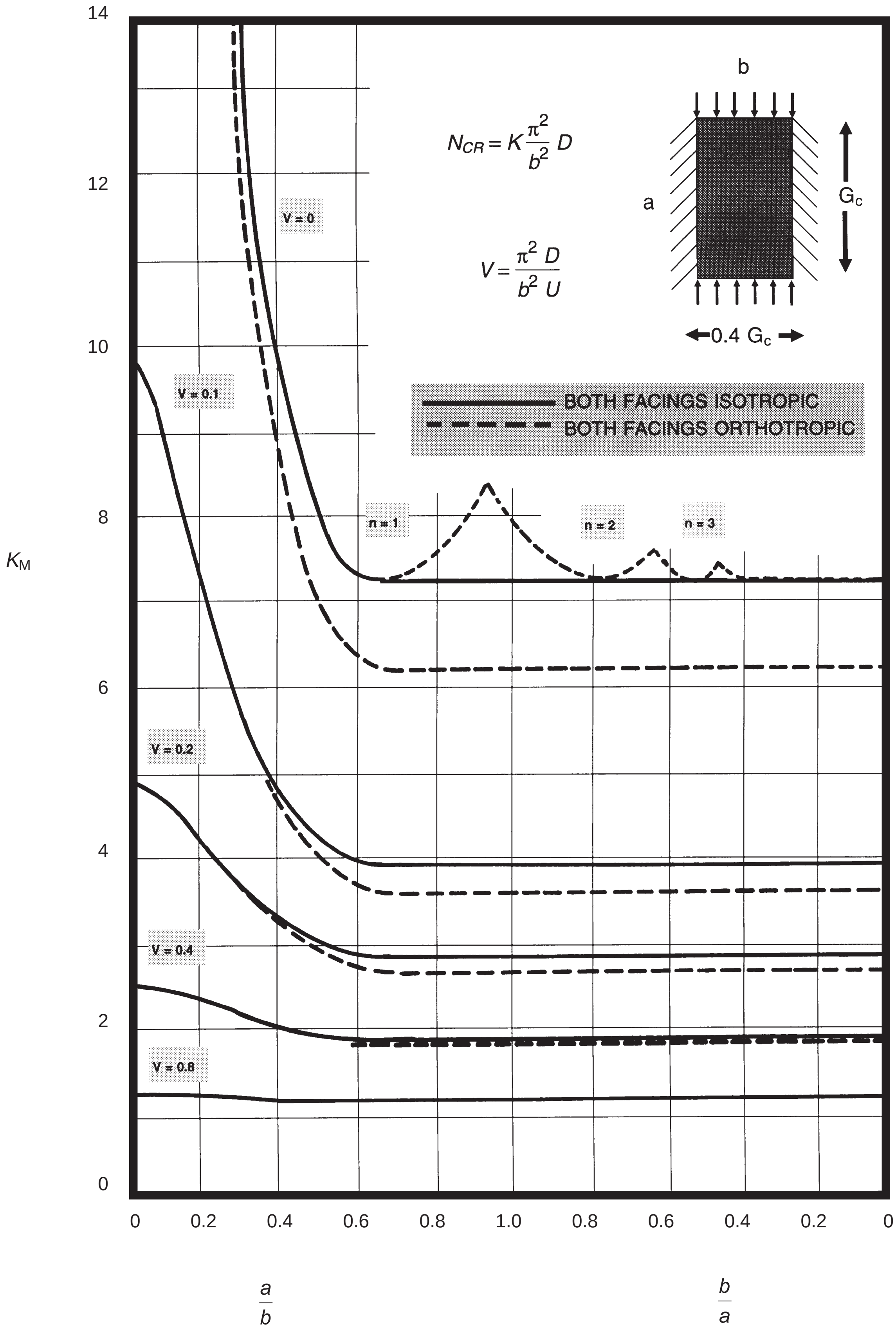


Figure 3-53 K_M for Sandwich Panels with Ends Simply Supported, Sides Clamped and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

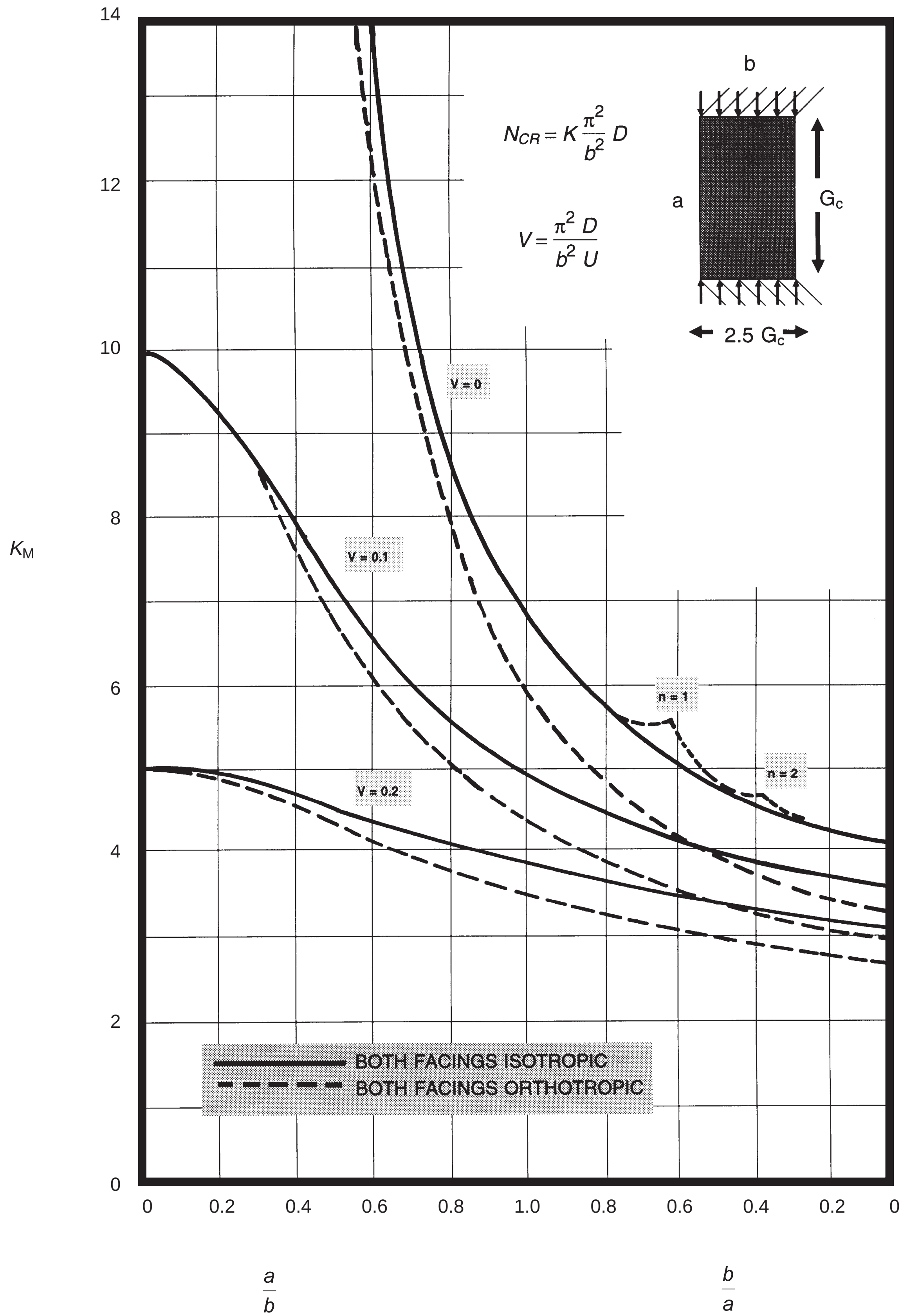


Figure 3-54 K_M for Sandwich Panels with Ends Clamped, Sides Simply Supported and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

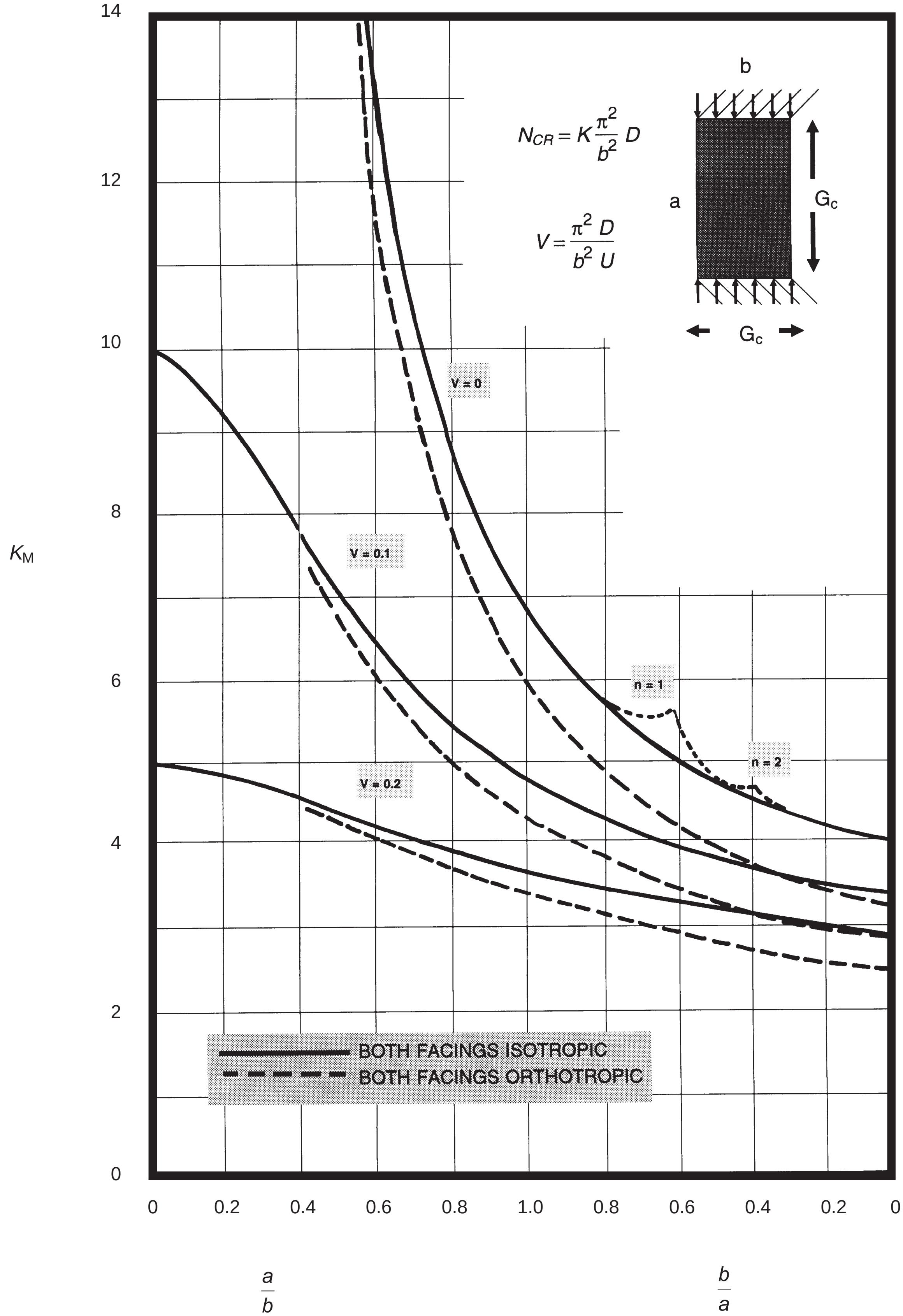


Figure 3-55 K_M for Sandwich Panels with Ends Clamped, Sides Simply Supported and Isotropic Core ($G_{Cb} = G_{Ca}$) [DDS 9110-9]

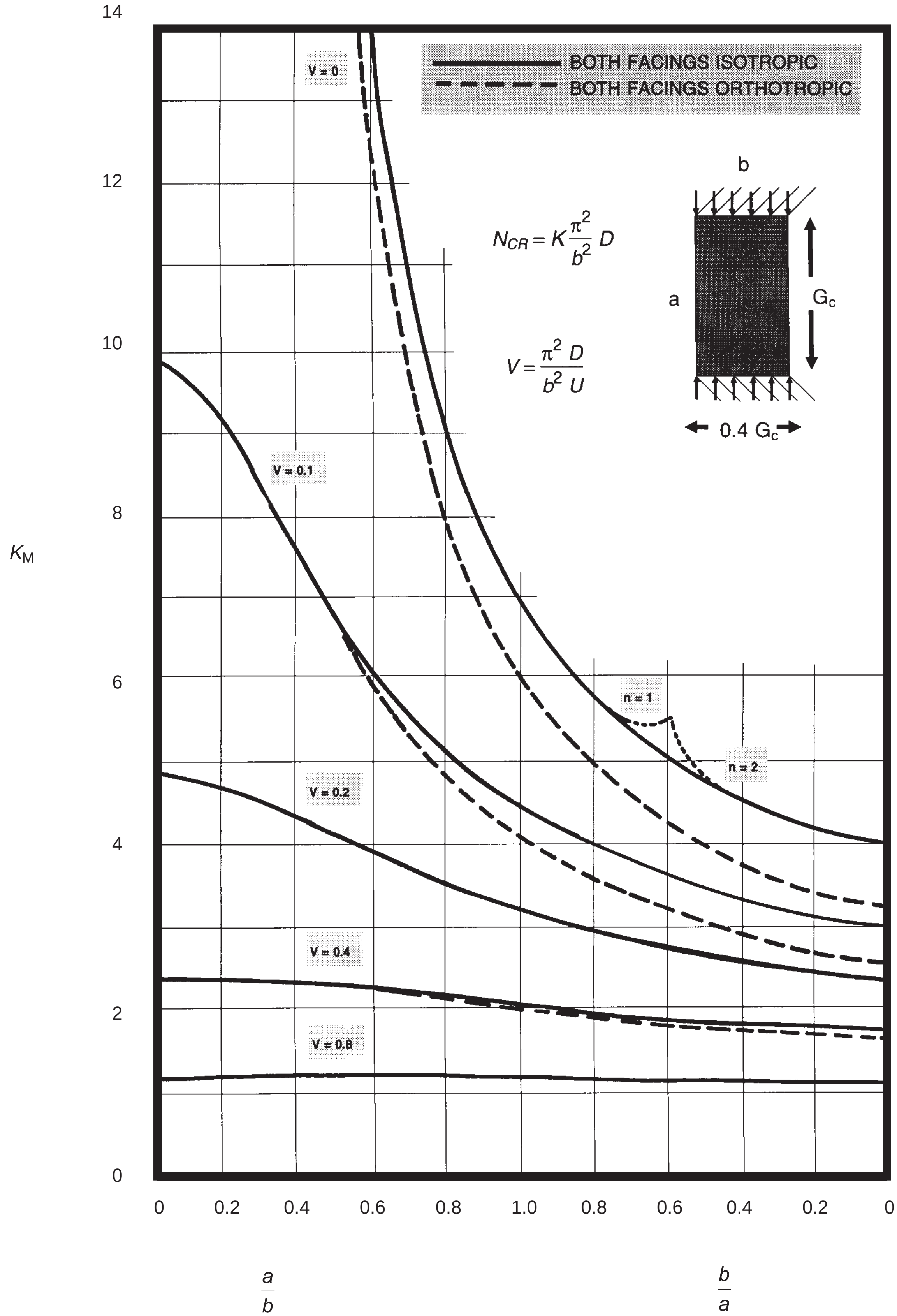


Figure 3-56 K_M for Sandwich Panels with Ends Clamped, Sides Simply Supported and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

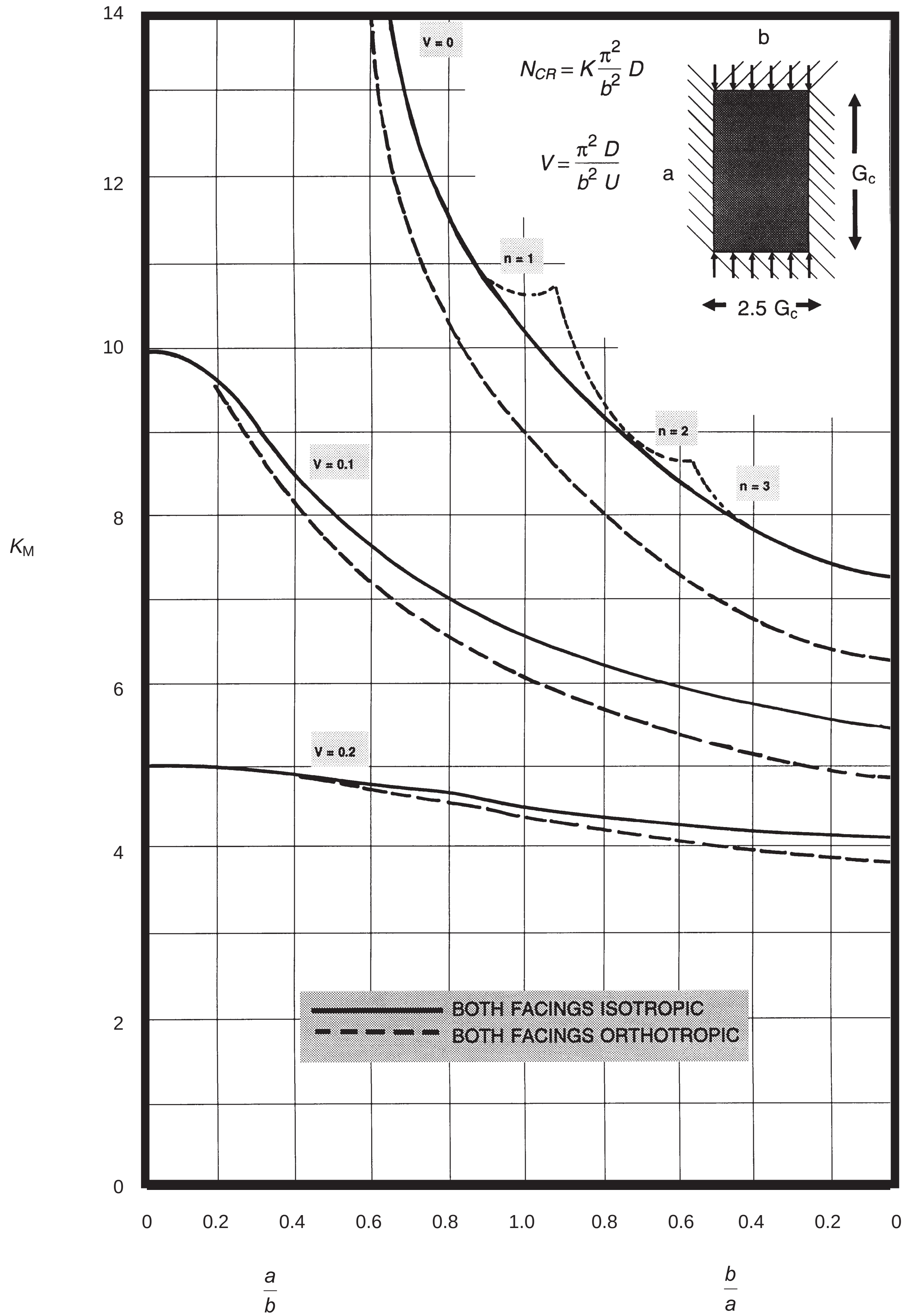


Figure 3-57 K_M for Sandwich Panels with Ends and Sides Clamped and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

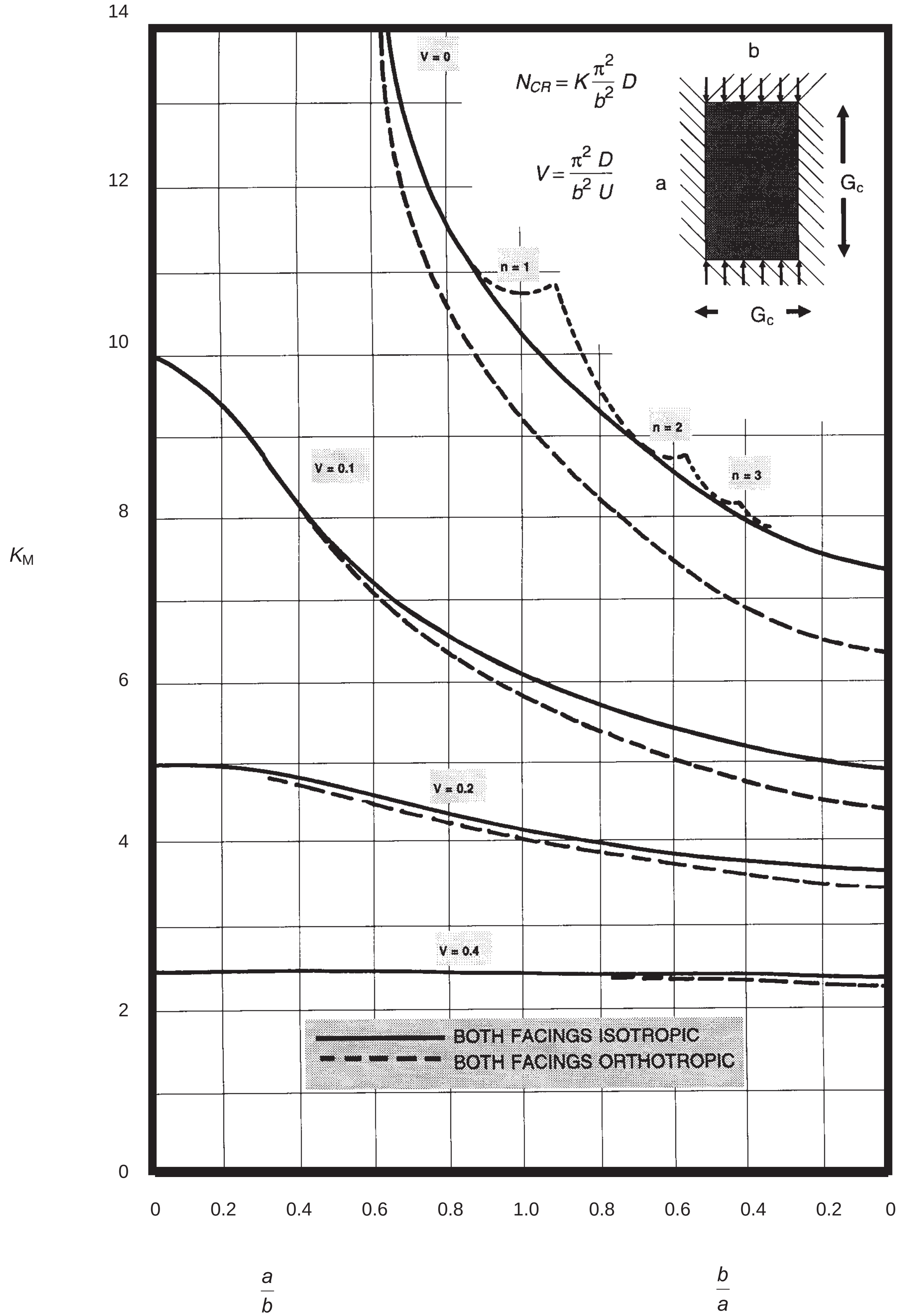


Figure 3-58 K_M for Sandwich Panels with Ends and Sides Clamped and Isotropic Core ($G_{Cb} = G_{Ca}$) [DDS 9110-9]

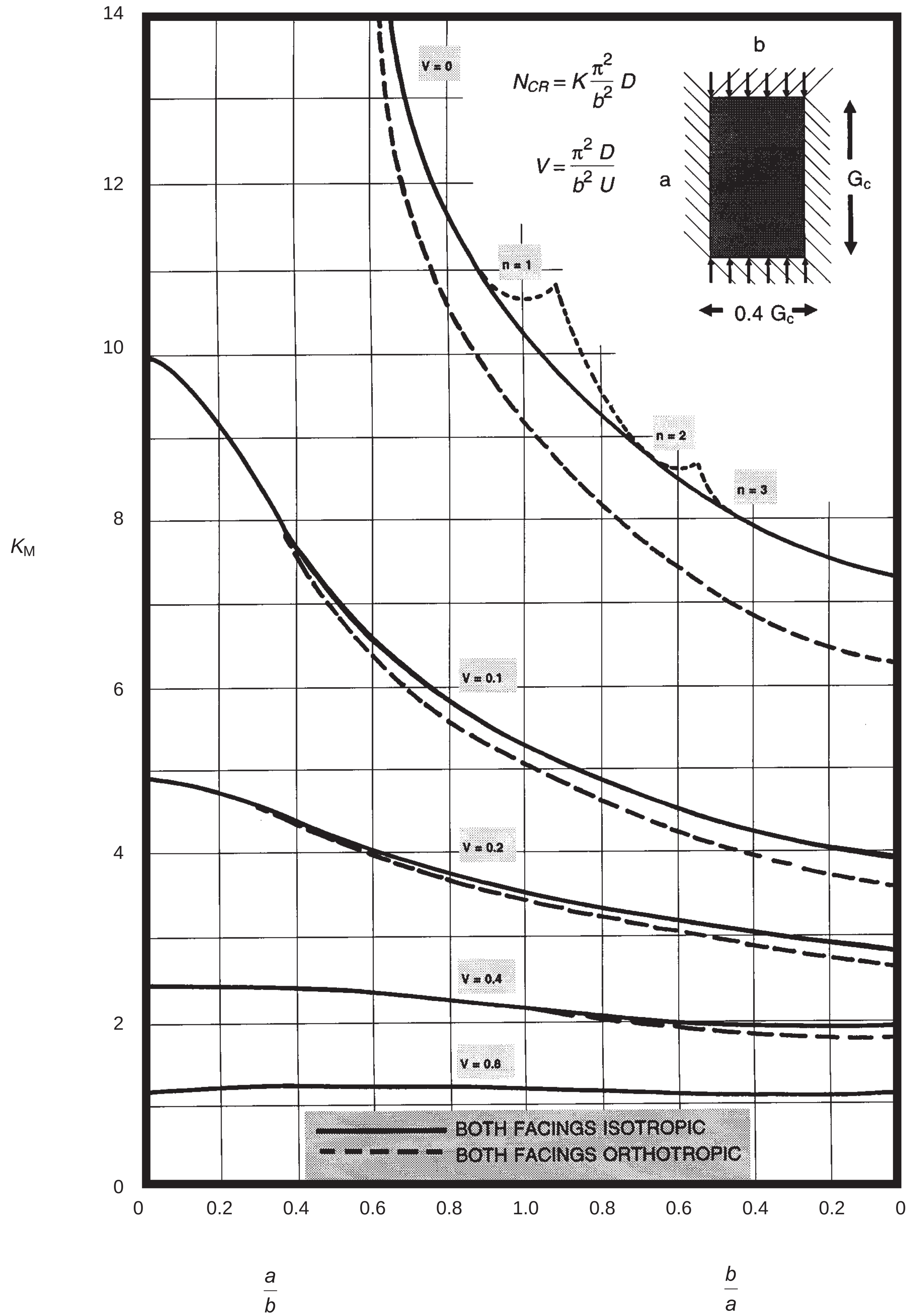


Figure 3-59 K_M for Sandwich Panels with Ends and Sides Clamped and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

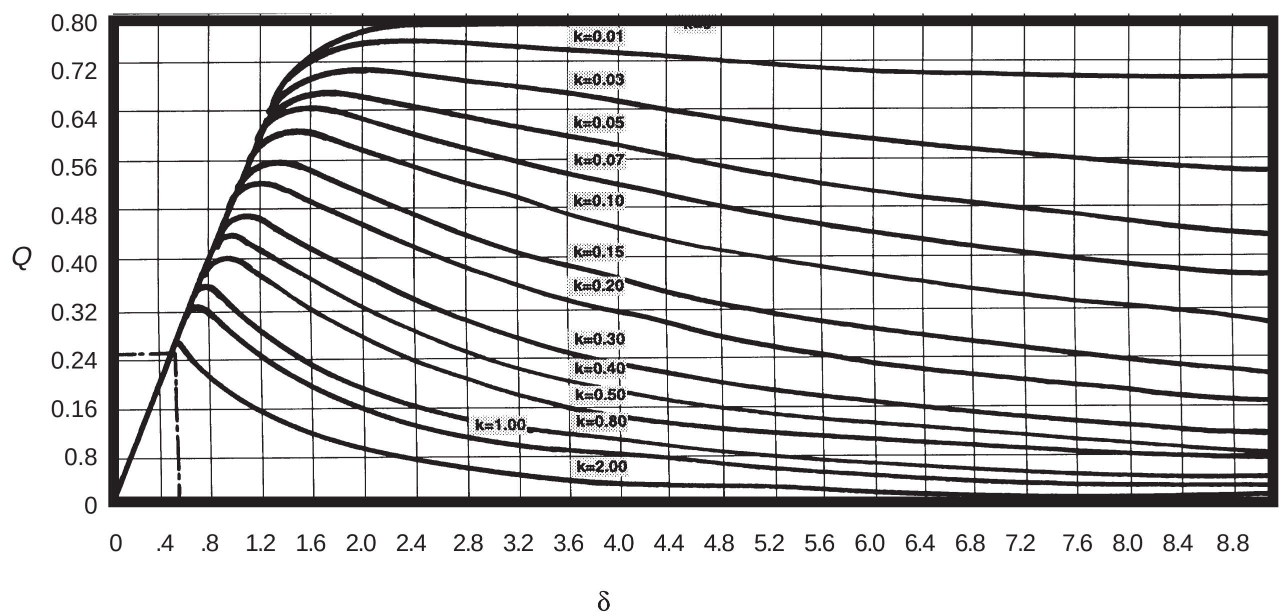


Figure 3-60 Parameters for Face Wrinkling Formulas [DDS 9110-9]

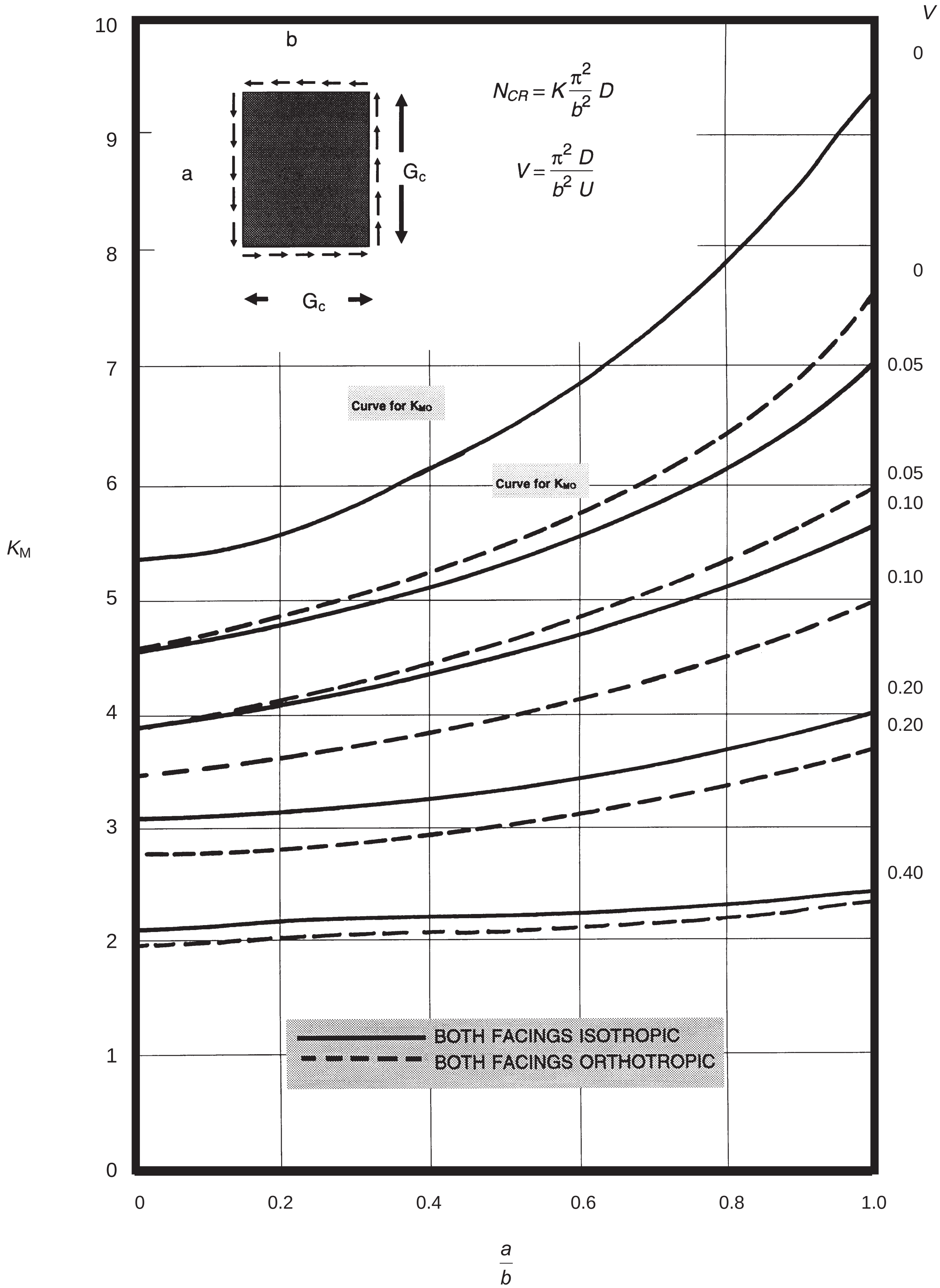


Figure 3-61 K_M for Sandwich Panels with All Edges Simply Supported and Isotropic Core [DDS 9110-9]

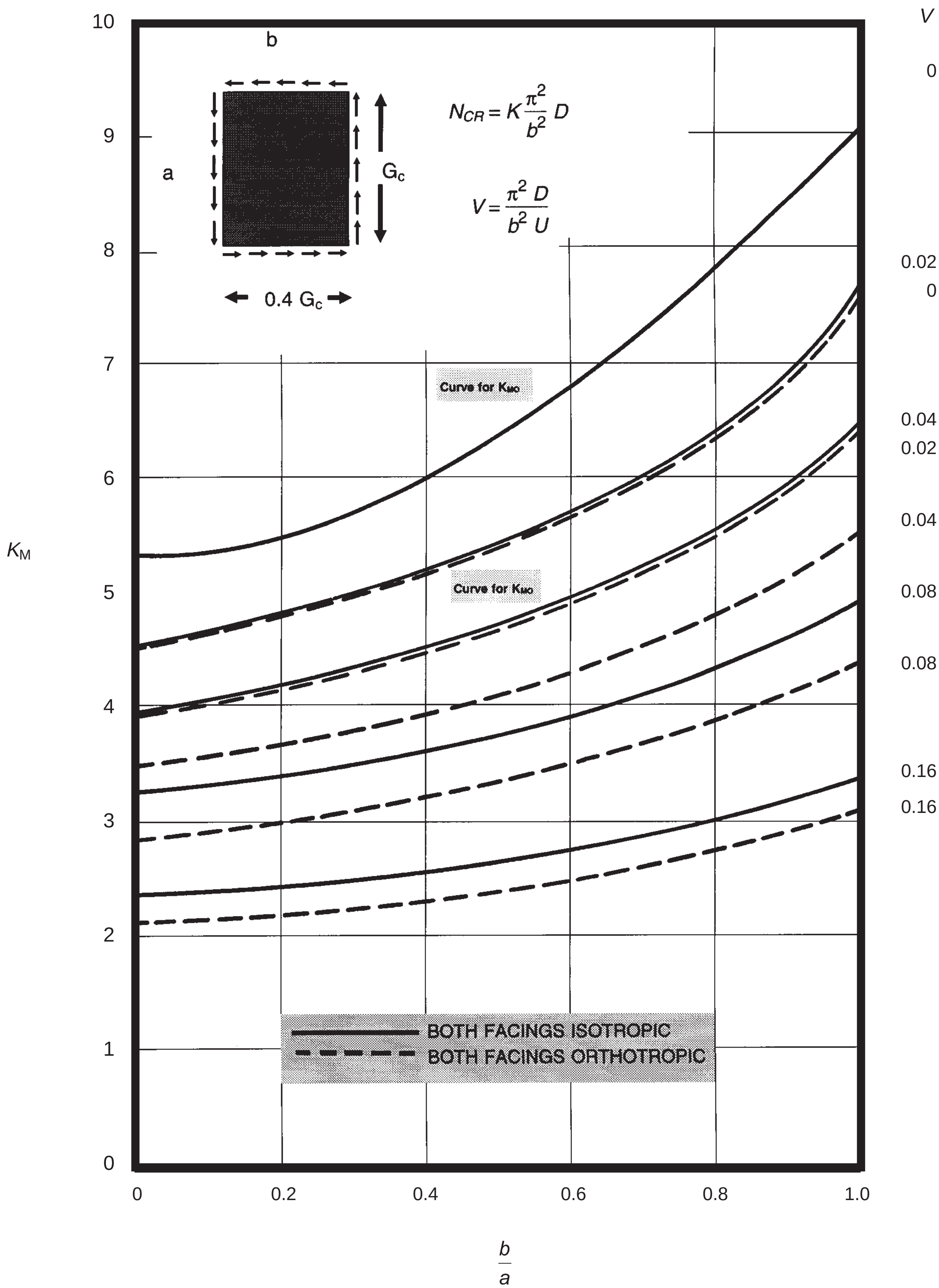


Figure 3-62 K_M for Sandwich Panels with All Edges Simply Supported and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

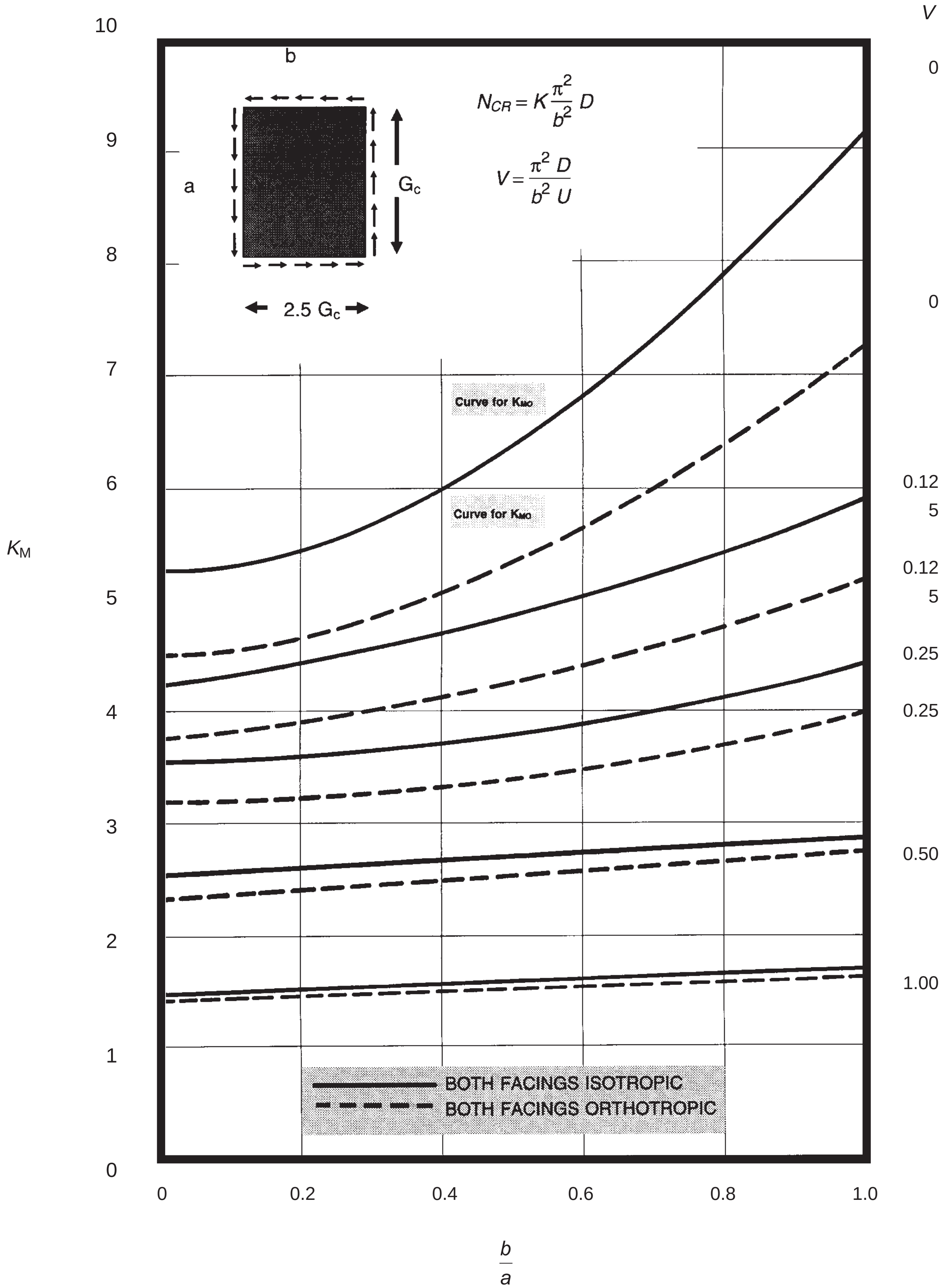


Figure 3-63 K_M for Sandwich Panels with All Edges Simply Supported and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

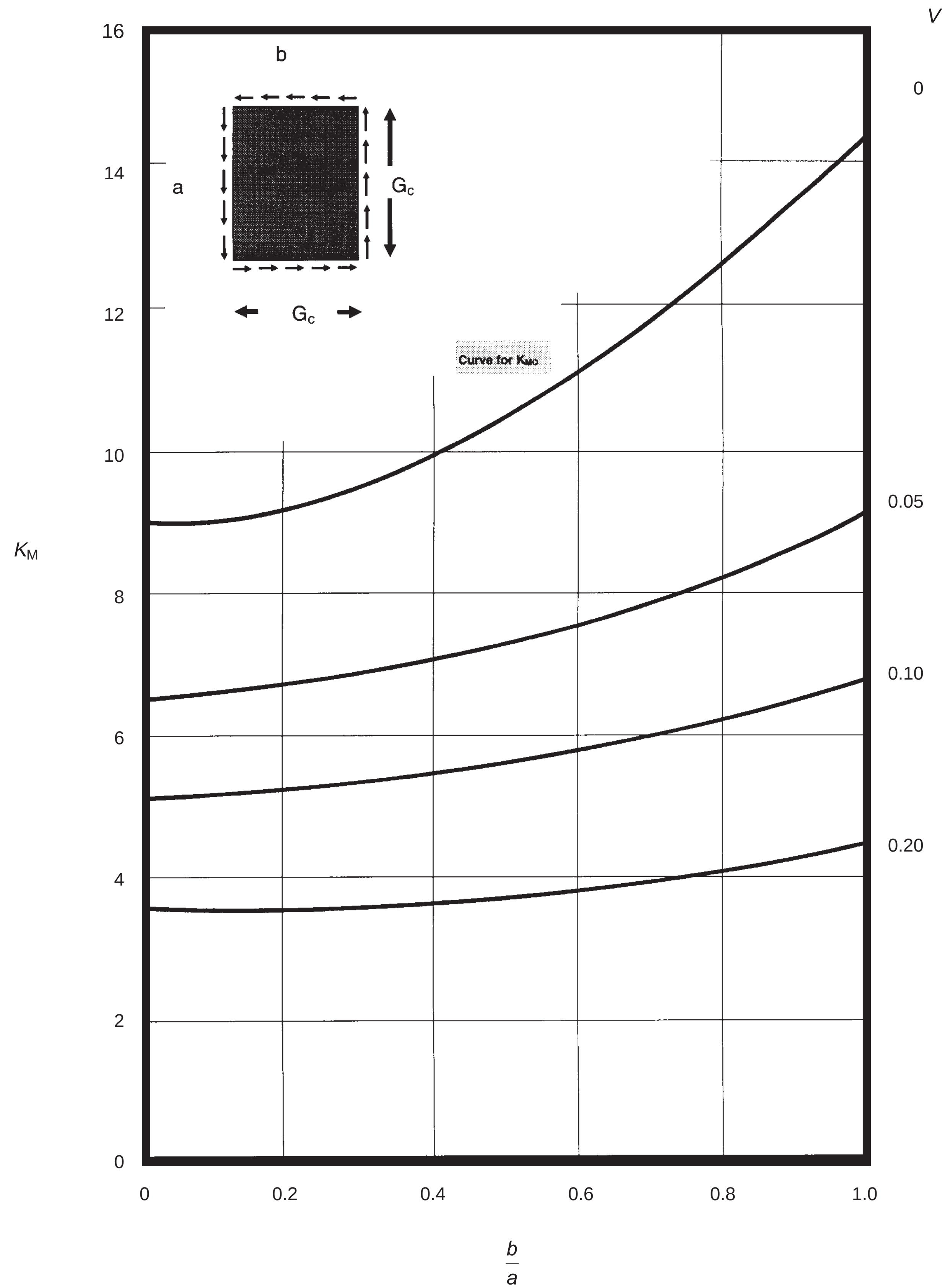


Figure 3-64 K_M for Sandwich Panels with All Edges Clamped, Isotropic Facings and Isotropic Core [DDS 9110-9]

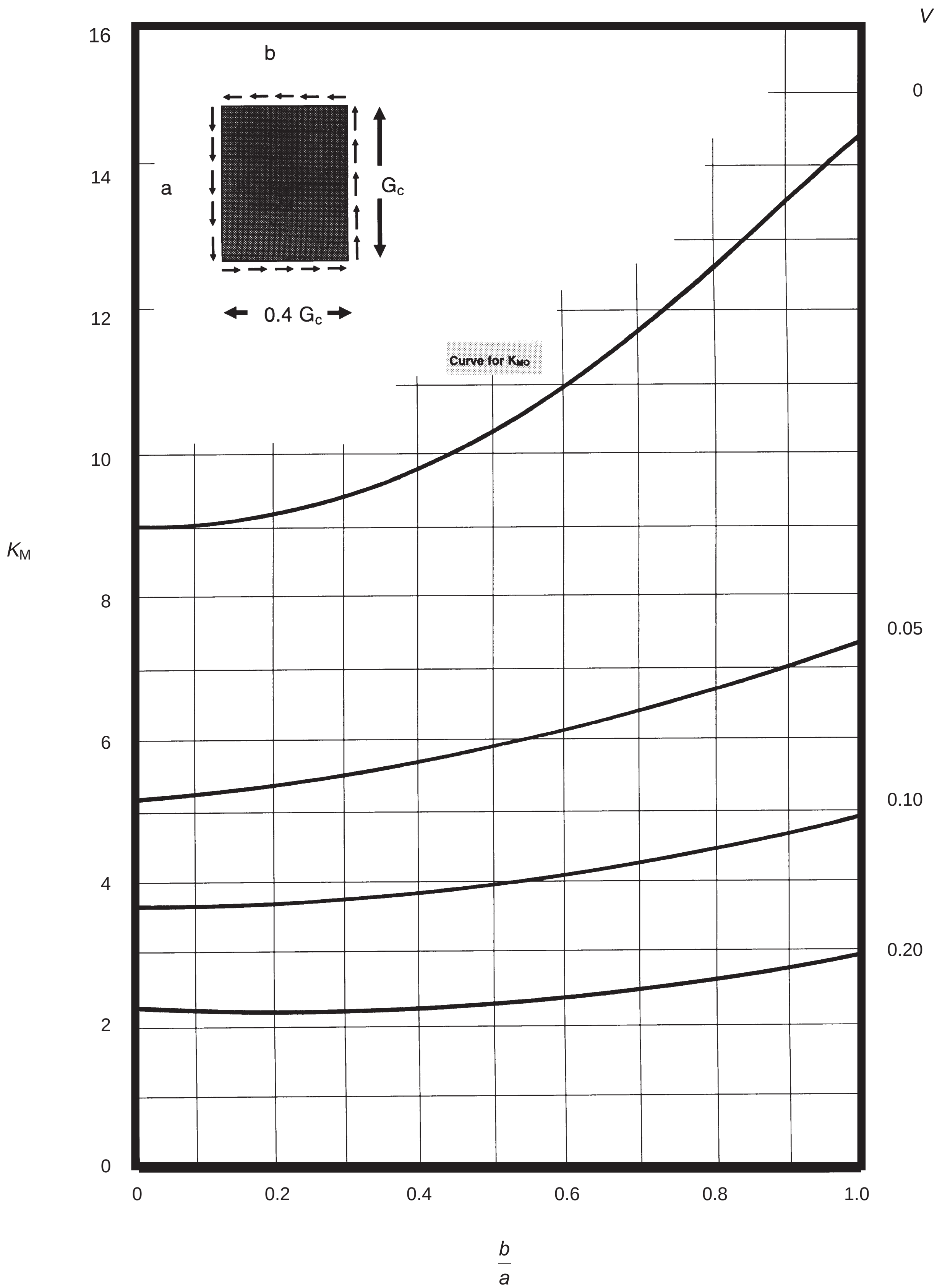


Figure 3-65 K_M for Sandwich Panels with All Edges Clamped, Isotropic Facings and Orthotropic Core (G_{Cb} = 0.4 G_{Ca}) [DDS 9110-9]

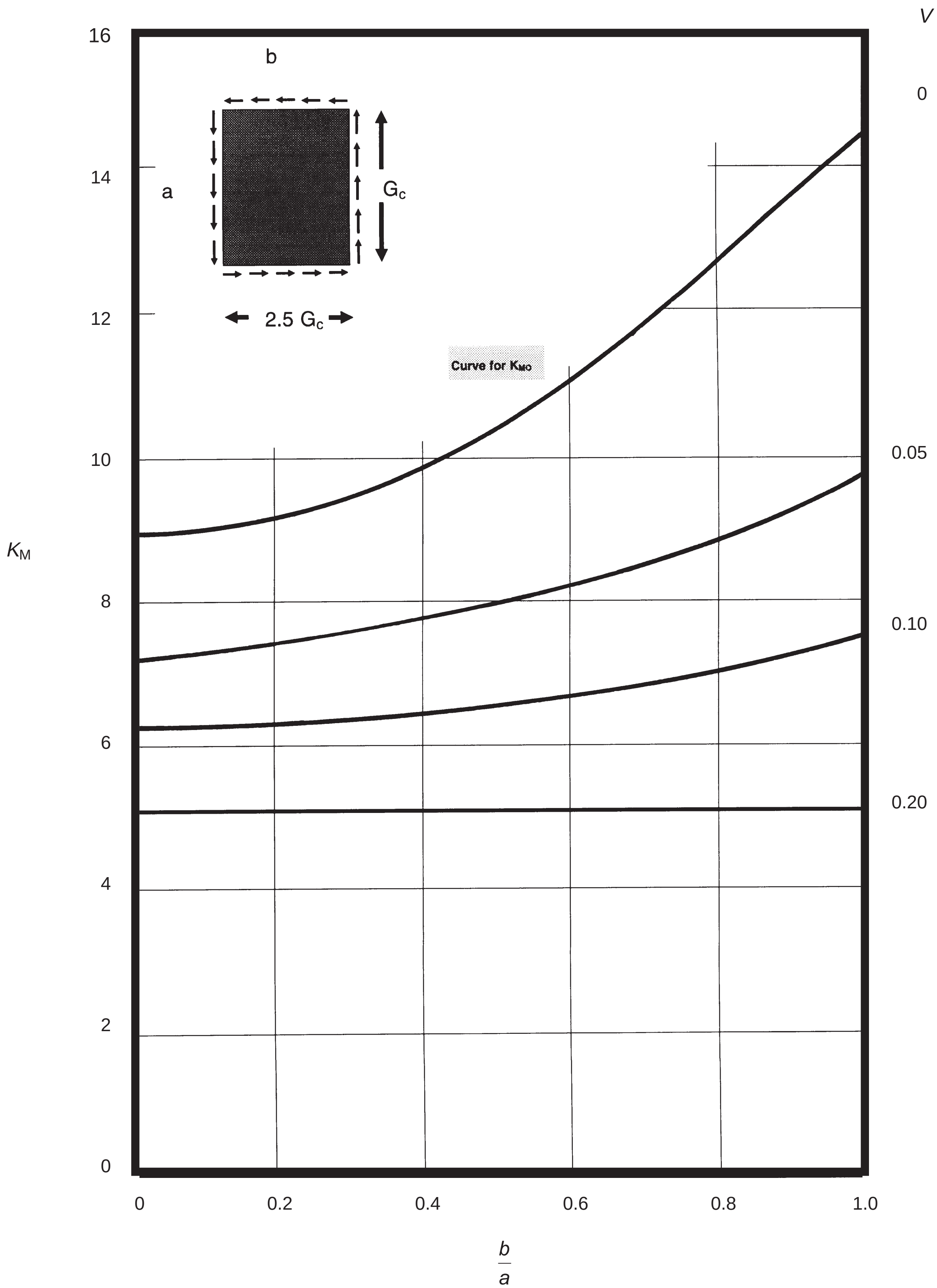


Figure 3-66 K_M for Sandwich Panels with All Edges Clamped, Isotropic Facings and Orthotropic Core (G_{Cb} = 2.5 G_{Ca}) [DDS 9110-9]

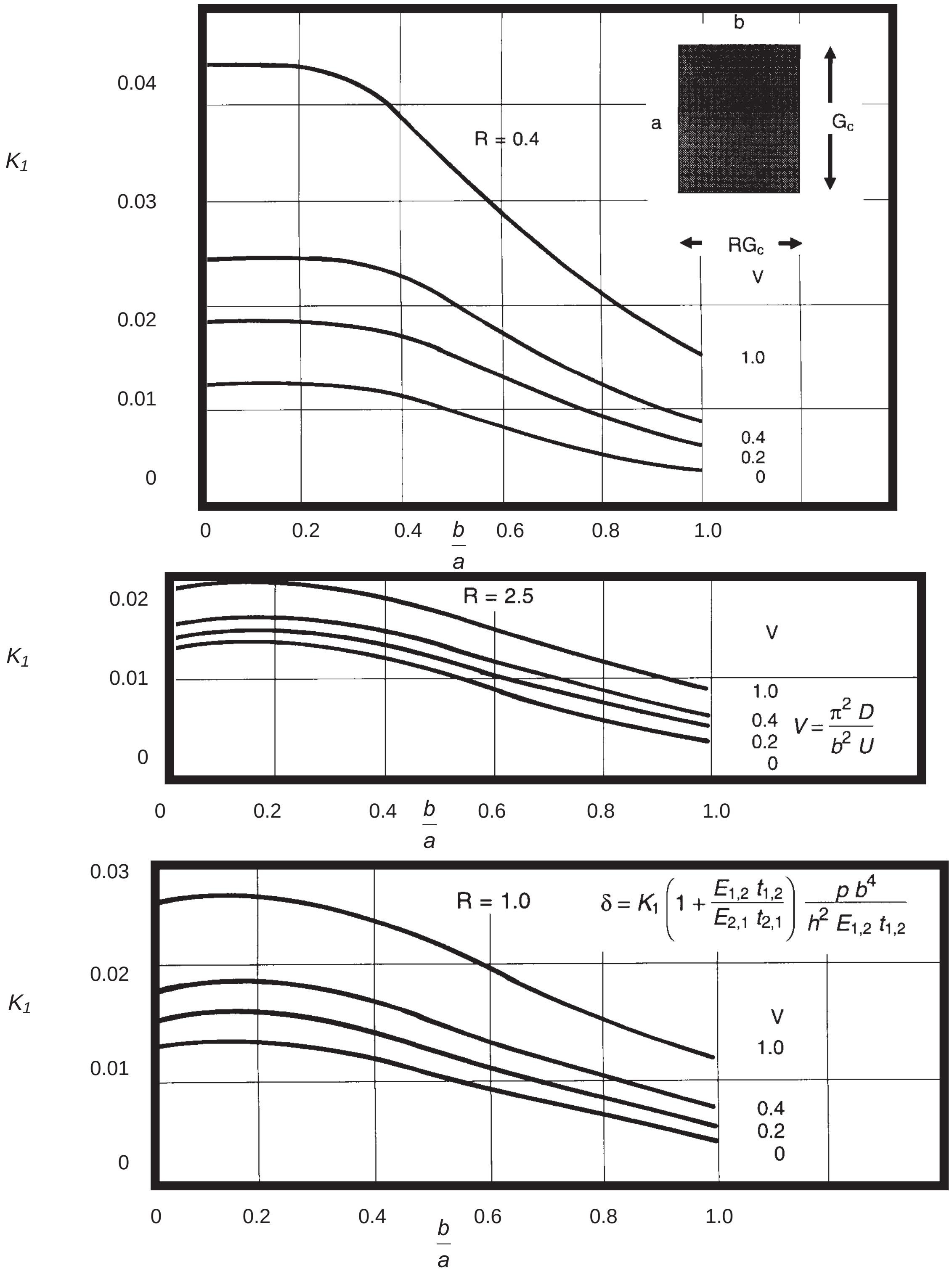


Figure 3-67 K_1 for Maximum Deflection, δ, of Flat, Rectangular Sandwich Panels with Isotropic Facings and Isotropic or Orthotropic Cores Under Uniform Loads [DDS 9110-9]

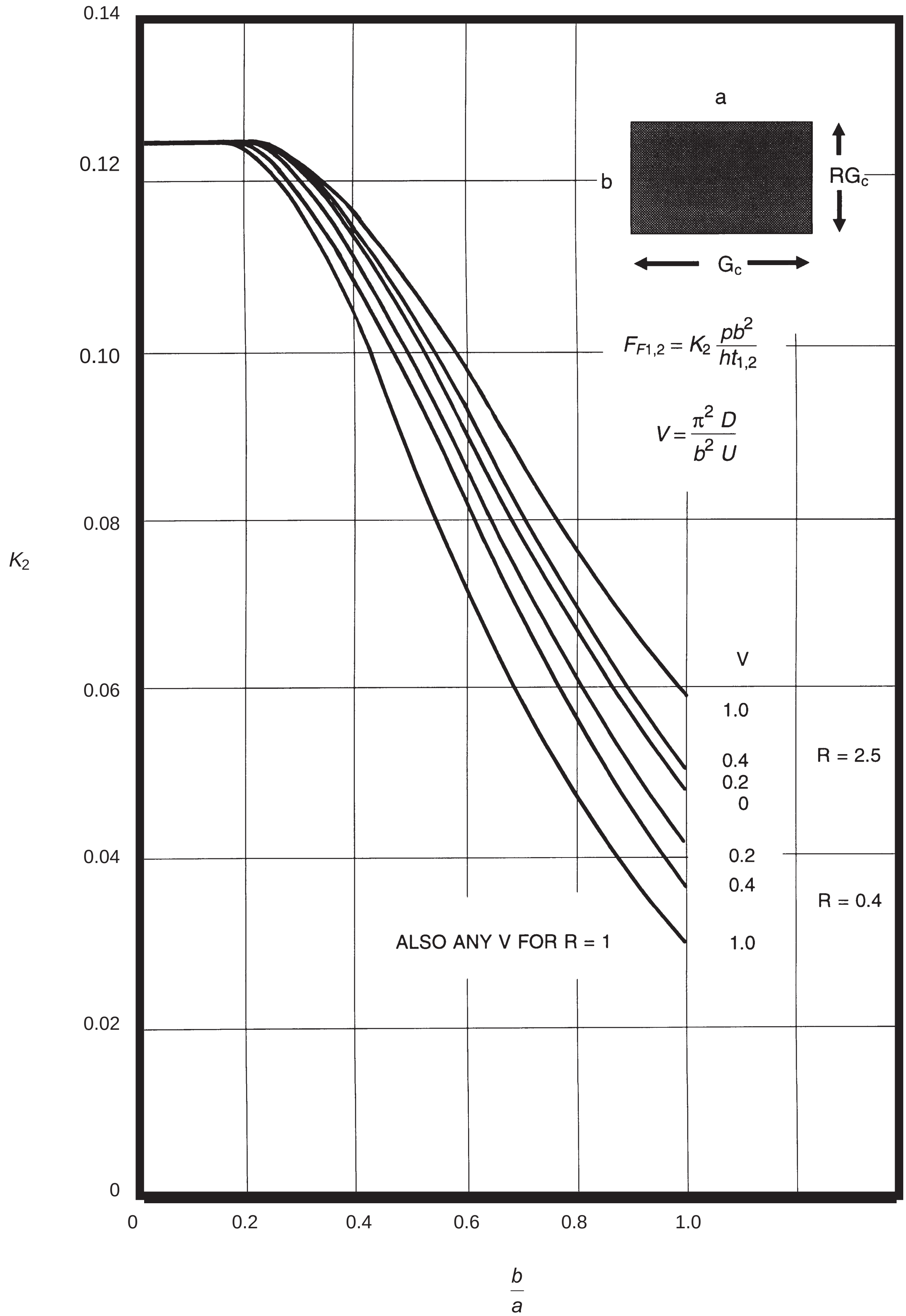


Figure 3-68 K_2 for Determining Face Stress, F_F of Flat, Rectangular Sandwich Panels with Isotropic Facings and Isotropic or Orthotropic Cores Under Uniform Loads [DDS 9110-9]

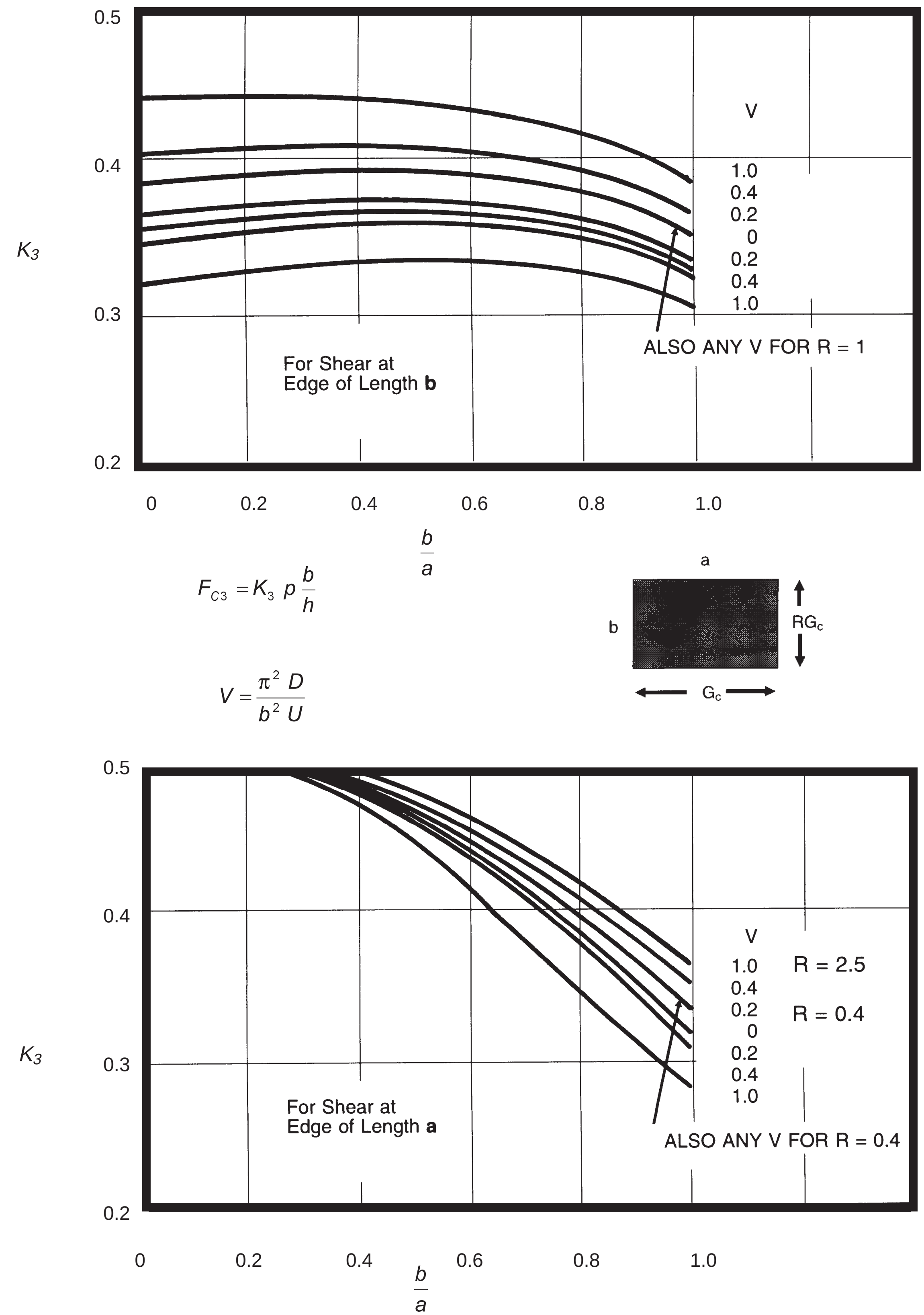


Figure 3-69 K_3 for Determining Maximum Core Shear Stress, F_{Cs}, for Sandwich Panels with Isotropic Facings and Isotropic or Orthotropic Cores Under Uniform Loads [DDS 9110-9]

Buckling of Transversely Framed Panels

FRP laminates generally have ultimate tensile and compressive strengths that are comparable with mild steel but stiffness is usually only 5% to 10%. A dominant design consideration then becomes elastic instability under compressive loading. Analysis of the buckling behavior of FRP grillages common in ship structures is complicated by the anisotrophic nature of the materials and the stiffener configurations typically utilized. Smith [3-17] has developed a series of data curves to make approximate estimates of the destabilizing stress, σ_x, required to produce catastrophic failure in transversely framed structures (see Figure 3-70).

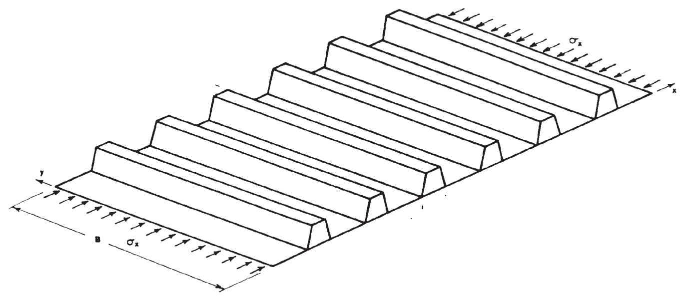


Figure 3-70 Transversely Stiffened Panel [Smith, *Buckling Problems in the Design of Fiberglass Reinforced Plastic Ships*]

The lowest buckling stresses of a transversely framed structure usually correspond to one of the interframe modes illustrated in Figure 3-71.

The first type of buckling (a) involves maximum flexural rotation of the shell/stiffener interface and minimal displacement of the actual stiffener.

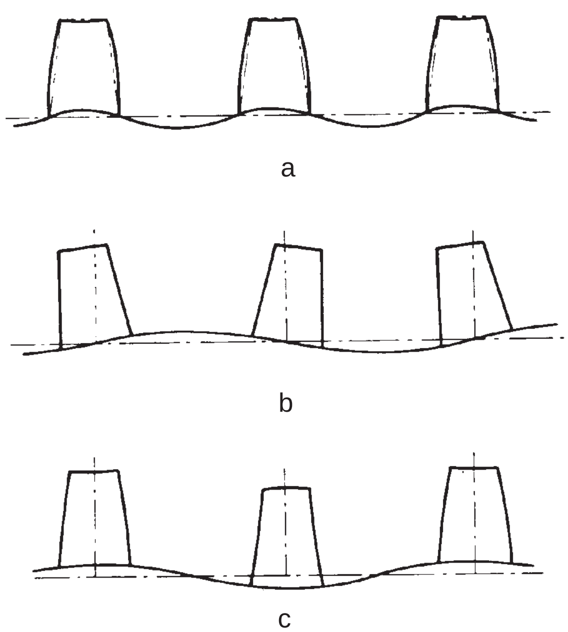


Figure 3-71 Interframe Buckling Modes [Smith, *Buckling Problems in the Design of Fiberglass Plastic Ships*]

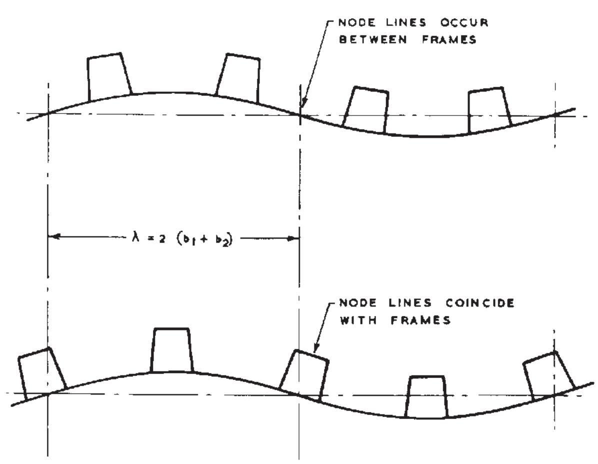


Figure 3-72 Extraframe Buckling Modes [Smith, *Buckling Problems in the Design of Fiberglass Plastic Ships*]

This action is dependent upon the restraining stiffness of the stiffener and is independent of the transverse span.

The buckling phenomena shown in (b) is the result of extreme stiffener rotation, and as such, is a function of transverse span which influences stiffener torsional stiffness.

The third type of interframe buckling depicted (c) is unique to FRP structures, but can often proceed the other failure modes. In this scenario, flexural deformation of the stiffeners produces bending of the shell plating at a half-wavelength coincident with the stiffener spacing. Large, hollow top-hat stiffeners can cause this effect. The restraining influence of the stiffener as well as the transverse span length are factors that control the onset of this type of buckling. All buckling modes are additionally influenced by the stiffener spacing and dimensions and the flexural rigidity of the shell.

Buckling of the structure may also occur at half-wavelengths greater than the spacing of the stiffeners. The next mode encountered is depicted in Figure 3-72 with nodes at or between stiffeners. Formulas for simply supported orthotropic plates show good agreement with more rigorous folded-plate analysis in predicting critical loads for this type of failure. [3-17] The approximate formula is:

$$N_{xcr} = \frac{\pi^2 D_y}{B^2}\left[\frac{D_1 B^2}{D_y \lambda^2} + \frac{2D_{xy}}{D_y} + \frac{\lambda^2}{B^2}\right] \qquad (3\text{-}85)$$

where:

N_{xcr} = critical load per unit width

D_y = flexural rigidity per unit width

D_1 = flexural rigidity of the shell in the x-direction

D_{xy} = stiffened panel rigidity = $\frac{1}{2}(C_x + C_y)$ with C_y = torsional rigidity per unit width and C_x = twisting rigidity of the shell (first term is dominant)

λ = buckling wavelength

Longitudinally framed vessels are also subject to buckling failure, albeit at generally higher critical loads. If the panel in question spans a longitudinal distance *L*, a suitable formula for estimating critical buckling stress, σ_{ycr}, based on the assumption of simply supported end conditions is:

$$\sigma_{ycr} = \frac{\dfrac{\pi^2 EI}{AL^2}}{1 + \dfrac{\pi^2 EI}{L^2 GA_s}} \qquad (3\text{-}86)$$

where:

EI = flexural rigidity of a longitudinal with assumed effective shell width

A = total cross-sectional area of the longitudinal including effective shell

GA_s = shear rigidity with A_s = area of the stiffener webs

Buckling failure can occur at reduced primary critical stress levels if the structure is subjected to orthogonal compressive stresses or high shear stresses. Areas where biaxial compression may occur include side shell where lateral hydrodynamic load can be significant or in way of frames that can cause secondary transverse stress. Areas of high shear stress include side shell near the neutral axis, bulkheads and the webs of stiffeners.

Large hatch openings are notorious for creating stress concentrations at their corners, where stress levels can be 3-4 times greater than the edge midspan. Large cut-outs reduce the compressive stability of the grillage structure and must therefore be carefully analyzed. Smith [3-17] has proposed a method for analyzing this portion of an FRP vessel whereby a plane-stress analysis is followed by a grillage buckling calculation to determine the distribution of destabilizing forces (see Figure 3-73). Figure 3-74 shows the first two global failure modes and associated average stress at the structure's mid-length.

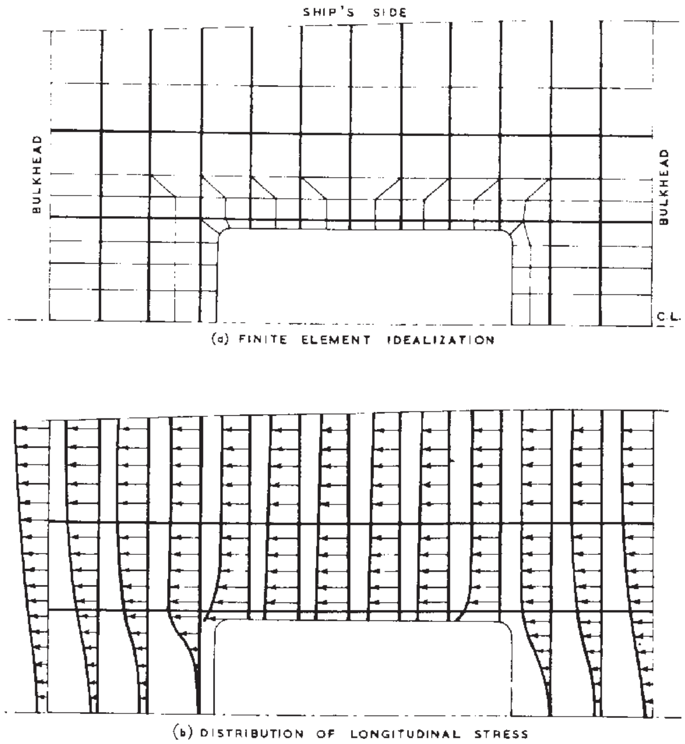


Figure 3-73 Plane Stress Analysis of Hatch Opening [Smith, Buckling Problems in the Design of Fiberglass Plastic Ships]

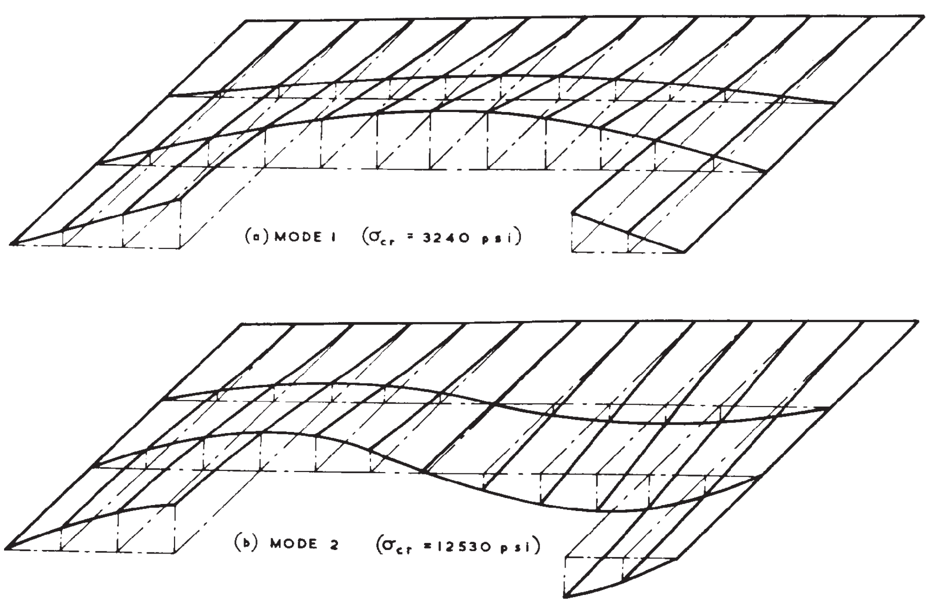


Figure 3-74 Deck Grillage Buckling Modes Near Hatch Opening [Smith, Buckling Problems in the Design of Fiberglass Plastic Ships]

Joints and Details

In reviewing the past four decades of FRP boat construction, very few failures can be attributed to the overall collapse of the structure due to primary hull girder loading. This is in part due to the fact that the overall size of FRP ships has been limited, but also because safety factors have been very conservative. In contrast to this, failures resulting from what is termed "local phenomena" have been observed in the early years of FRP development. As high-strength materials are introduced to improve vessel performance, the safety cushion associated with "bulky" laminates diminishes. As a consequence, the FRP designer must pay careful attention to the structural performance of details.

Details in FRP construction can be any area of the vessel where stress concentrations may be present. These typically include areas of discontinuity and applied load points. As an example, failures in hull panels generally occur along their edge, rather than the center. [3-18] FRP construction is particularly susceptible to local failure because of the difficulty in achieving laminate quality equal to a flat panel. Additionally, stress concentration areas typically have distinct load paths which must coincide with the directional strengths of the FRP reinforcing material. With the benefit of hindsight knowledge and a variety of reinforcing materials available today, structural detail design can rely less on "brute force" techniques.

Secondary Bonding

FRP structures will always demonstrate superior structural properties if the part is fabricated in one continuous cycle without total curing of intermediate plies. This is because interlaminar properties are enhanced when a chemical as well as mechanical bond is present. Sometimes the part size, thickness or manufacturing sequence preclude a continuous lay-up, thus requiring the application of wet plies over a previously cured laminate, known as secondary bonding. Much of the test data available on secondary bonding performance dates back to the early 1970's when research was active in support of FRP minesweeper programs. Frame and bulkhead connections were targeted as weak points when large hulls were subjected to extreme shock from detonated charges. Reports on secondary bond strength by Owens-Corning Fiberglas [3-19] and Della Rocca & Scott [3-20] are summarized below:

- Failures were generally cohesive in nature and not at the bond interface line. A clean laminate surface at the time of bonding is essential and can best be achieved by use of a peeling ply. A peeling ply consists of a dry piece of reinforcement (usually cloth) that is laid down without being wetted out. After cure, this strip is peeled away, leaving a rough bonding surface with raised glass fibers;
- Filleted joints proved to be superior to right-angle joints in fatigue tests. It was postulated that the bond angle material was stressed in more of a pure flexural mode for the radiused geometry;
- Bond strengths between plywood and FRP laminates is less than that of FRP itself. Secondary mechanical fasteners might be considered;
- In a direct comparison between plywood frames and hat-sectioned stiffeners, the stiffeners appear to be superior based on static tests; and
- Chopped strand mat offers a better secondary bond surface than woven roving.

Table 3-6 Secondary Bond Technique Desirability [Della Rocca and Scott, *Materials Test Program for Application of Fiberglass Plastics to U.S.. Navy Minesweepers*]

Preferable Bonding Techniques	Acceptable Bonding Techniques	Undesirable Procedures
Bond resin: either general purpose or fire retardant, resilient	Bond resin: general purpose or fire retardant, rigid air inhibited	No surface treatment
Surface treatment: roughened with a pneumatic saw tooth hammer, peel ply, or continuous cure of rib to panel; one ply of mat in way of bond	Surface treatment: rough sanding	Excessive stiffener faying flange thickness
Stiffener faying flange thickness: minimum consistent with rib strength requirement		
Bolts or mechanical fasteners are recommended in areas of high stress		

Hull to Deck Joints

Since the majority of FRP vessels are built with the deck and hull coming from different molds, the builder must usually decide on a suitable technique for joining the two. Since this connection is at the extreme fiber location for both vertical and transverse hull girder loading, alternating tensile and compressive stresses are expected to be at a maximum. The integrity of this connection is also responsible for much of the torsional rigidity exhibited by the hull. Secondary deck and side shell loading shown in Figure 3-75 is often the design limiting condition. Other design considerations include: maintaining watertight integrity under stress, resisting local impact from docking,

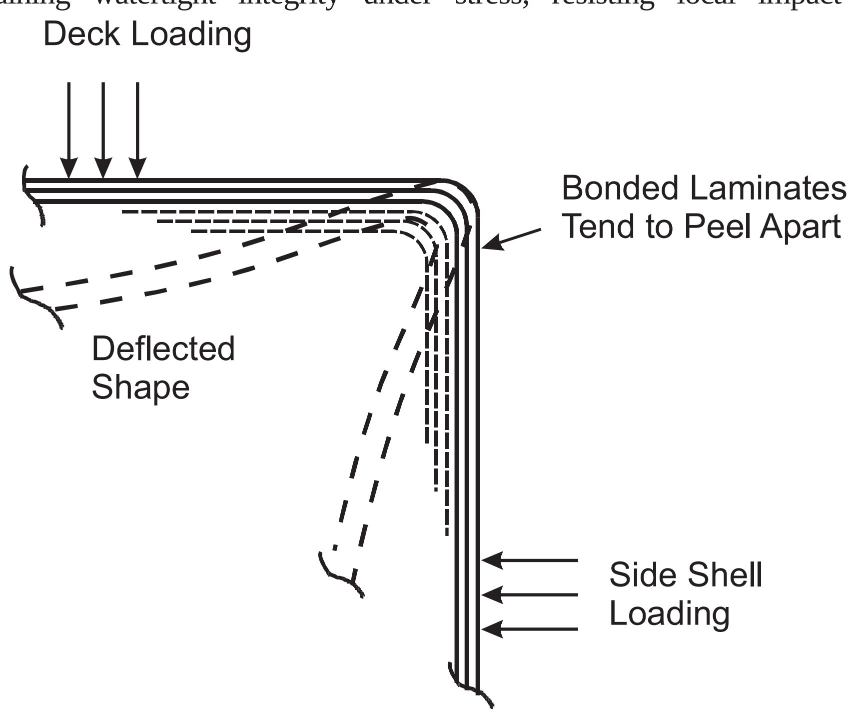


Figure 3-75 Deck Edge Connection - Normal Deck and Shell Loading Produces Tension at the Joint [Gibbs and Cox, ***Marine Design Manual for FRP***]

personnel footing assistance, and appearance (fairing of shear). Figure 3-76 shows typical failure modes for traditional sandwich construction with tapered cores. A suggested method for improving hull-to-deck joints is also presented. Transfer of shear loads between inner and outer skins is critical. Note that the lap joint, which used a methacrylate adhesive with a shear strength of 725 psi (50 kg/cm^2) did not fail. This compares with polyester resin, which will typically provide 350 psi (24 kg/cm^2) and epoxy resin, which provides 500 psi (34.5 kg/cm^2) shear strength. [3-21]

Improved Hull to Deck Joint

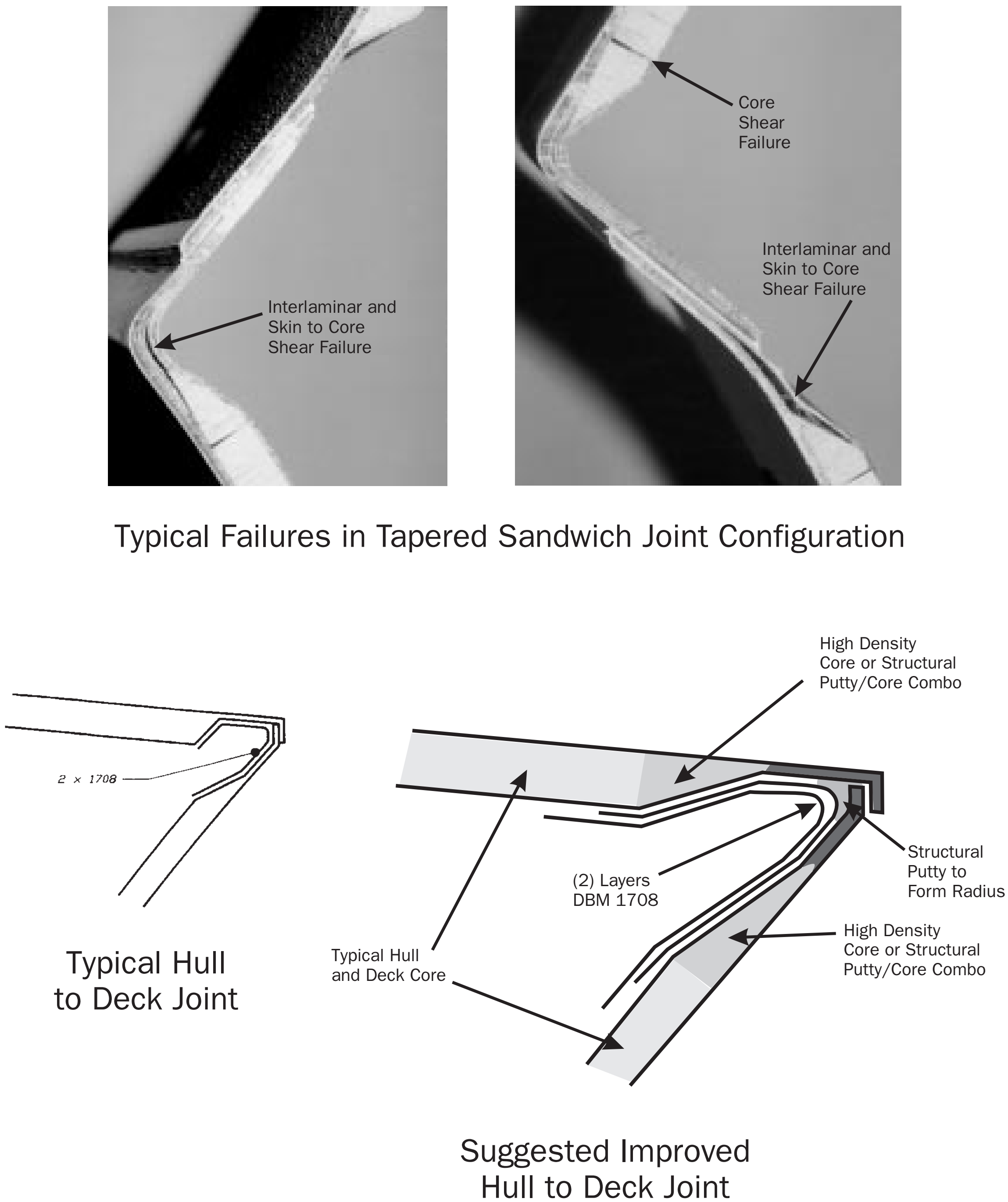


Figure 3-76 Improved Hull to Deck Joint for Sandwich Core Production Vessels

Bulkhead Attachment

The scantlings for structural bulkheads are usually determined from regulatory body requirements or first principals covering flooding loads and in-plane deck compression loads. Design principals developed for hull panels are also relevant for determining required bulkhead strength. Of interest in this section is the connection of bulkheads or other panel stiffeners that are normal to the hull surface. In addition to the joint strength, the strength of the bulkhead and the hull in the immediate area of the joint must be considered. Other design considerations include:

- Some method to avoid creation of a “hard” spot should be used;
- Stiffness of joint should be consistent with local hull panel;
- Avoid laminating of sharp, 90^o corners;
- Geometry should be compatible with fabrication capabilities; and
- Cutouts should not leave bulkhead core material exposed.

An acceptable configuration for use with solid FRP hulls is shown in Figure 3-77. As a general rule, tape-in material should be at least 2 inches (50 mm) or 1.4 × *fillet radius* along each leg; have a thickness half of the solid side shell; taper for a length equal to at least three times the tape-in thickness; and include some sort of fillet material. Double bias knitted tapes with or without a mat backing are excellent choices for tape-in material. With primary reinforcement oriented at 45^o, all fiberglass adds to the strength of the joint, while at the same time affording more flexibility. Figure 3-78 shows both double-bias tape-in versus conventional woven roving tape-in. When building up layers of reinforcements that have varying widths, it is best to place the narrowest plies on the bottom and work toward increasingly wide reinforcements. This reduces the amount of exposed edges.

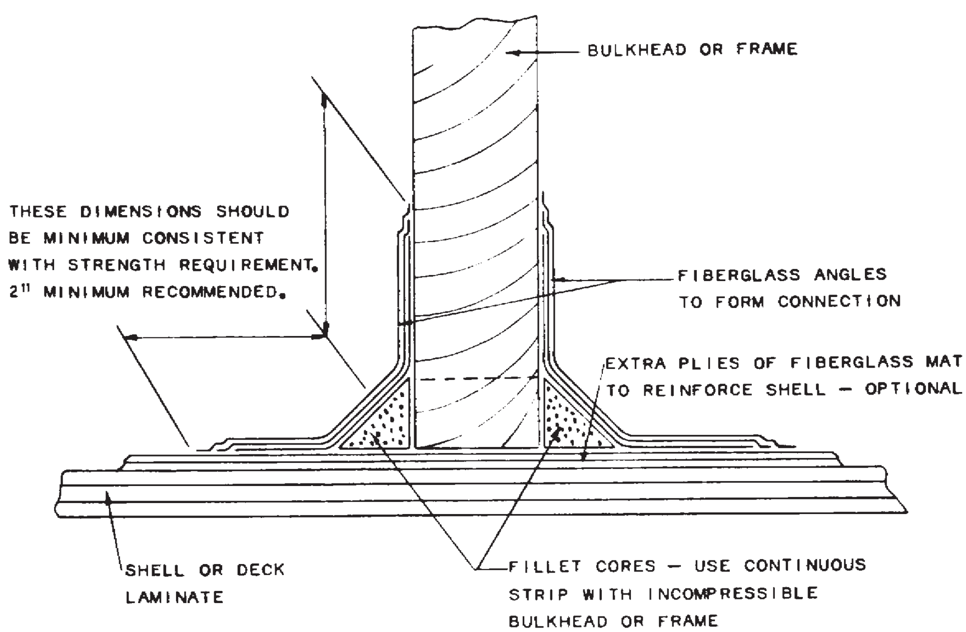


Figure 3-77 Connection of Bulkheads and Framing to Shell or Deck [Gibbs and Cox, ***Marine Design Manual for FRP***]

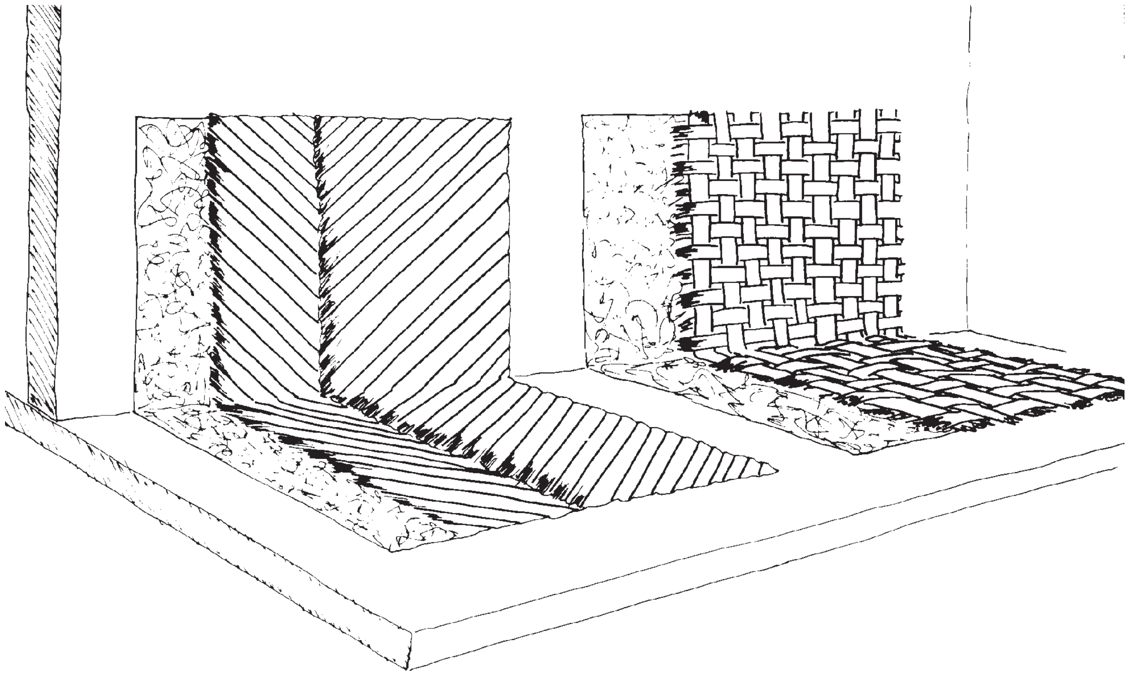


Figure 3-78 Double Bias and Woven Roving Bulkhead Tape-In [Knytex]

Stringers

Stringers in FRP construction can either be longitudinal or transverse and usually have a non-structural core that serves as a form. In general, continuity of longitudinal members should be maintained with appropriate cut-outs in transverse members. These intersections should be completely bonded on both the fore and aft side of the transverse member with a laminate schedule similar to that used for bonding to the hull.

Traditional FRP design philosophy produced stiffeners that were very narrow and deep to take advantage of the increased section modulus and stiffness produced by this geometry. The current trend with high-performance vehicles is toward shallower, wider stiffeners that reduce effective panel width and minimize stress concentrations. Figure 3-79 shows how panel span can be reduced with a low aspect ratio stiffener. Some builders are investigating techniques to integrally mold in stiffeners along with the hull's primary inner skin, thus eliminating secondary bonding problems altogether.

Regulatory agencies, such as ABS, typically specify stiffener scantlings in terms of required section moduli and moments of inertia. [3-6, 3-7, 3-22] Examples of a single skin FRP stiffener and a high-strength material stiffener with a cored panel are presented along with sample property calculations to illustrate the design process. These examples are taken from USCG NVIC No. 8-87. [3-22]

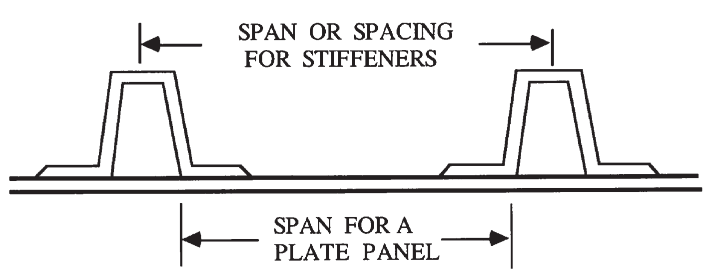


Figure 3-79 Reference Stiffener Span Dimensions [Al Horsmon, USCG NVIC No. 8-87]

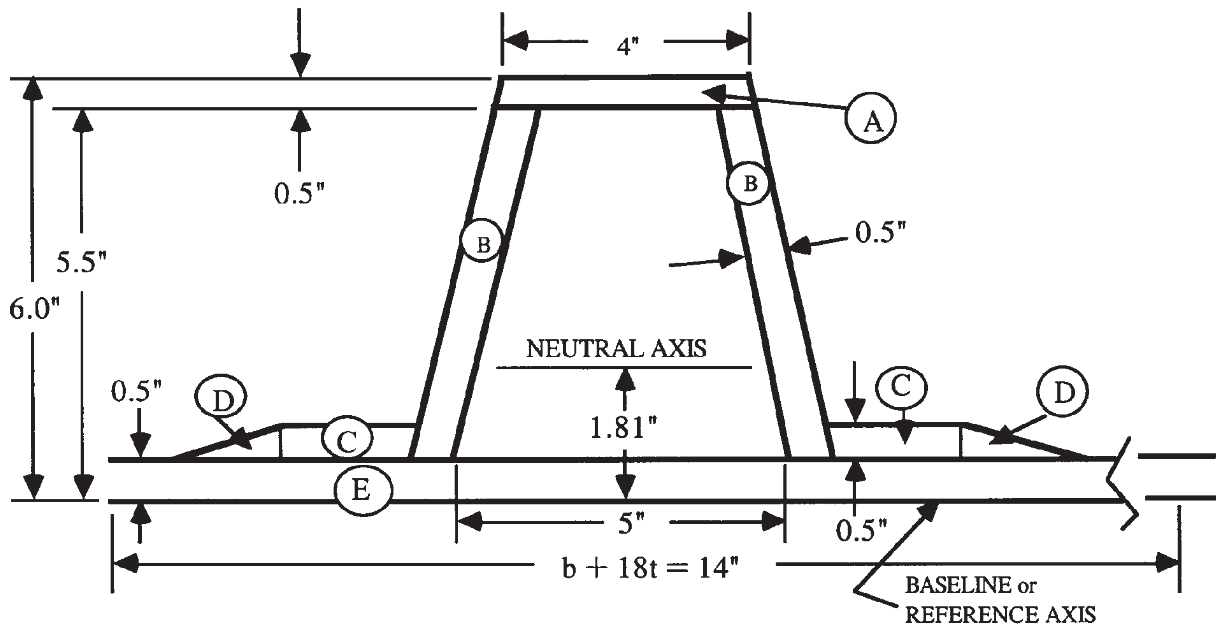


Figure 3-80 Stringer Geometry for Sandwich Construction [Al Horsmon, USCG NVIC No. 8-87]

Table 3-7 Example Calculation for Single Skin Stiffener

Item	b	h	A = b x h	d	Ad	Ad^2	i_o
A	4.00	0.50	2.00	5.75	11.50	66.13	0.04
B	0.50	5.10	2.55	3.00	7.65	23.95	5.31
B	0.50	5.10	2.55	3.00	7.65	23.95	5.31
C	2.00	0.50	1.00	0.75	0.75	0.56	0.02
C	2.00	0.50	1.00	0.75	0.75	0.56	0.02
D	3.00	0.50	0.75	0.67	0.50	0.33	0.01
E	14.00	0.50	7.00	0.25	1.75	0.44	0.15
	Totals:		16.85		30.55	115.92	10.86

$$d_{NA} = \frac{\sum Ad}{\sum A} = \frac{30.55}{16.85} = 1.81 \text{ inches} \quad (3\text{-}87)$$

$$I_{NA} = \sum i_o + \sum Ad^2 - [\ Ad^2\ ] = 10.86 + 115.92 - [16.85 \times (1.81)^2] = 71.58 \quad (3\text{-}88)$$

$$SM_{top} = \frac{I}{d_{NA\ top}} = \frac{71.58}{4.19} = 17.08 \text{ in}^3 \quad (3\text{-}89)$$

$$SM_{bottom} = \frac{I}{d_{NA\ bottom}} = \frac{71.58}{1.81} = 39.55 \text{ in}^3 \quad (3\text{-}90)$$

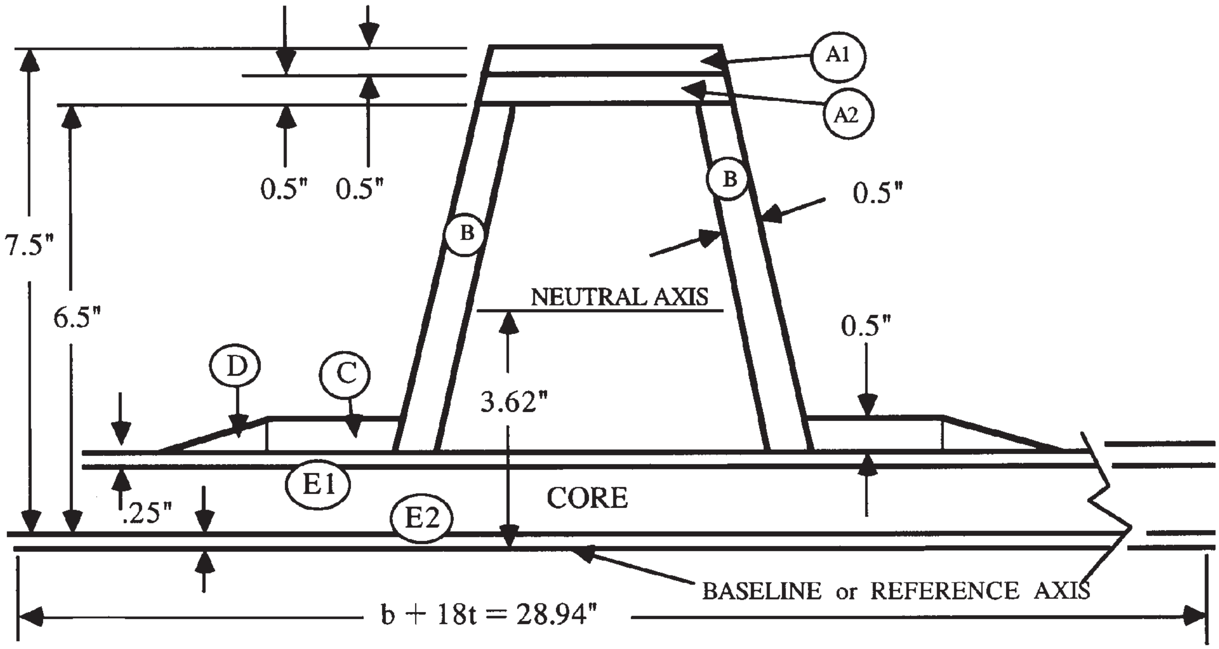


Figure 3-81 Stringer Geometry including High-Strength Reinforcement (3" wide layer of Kevlar® in the top) [Al Horsmon, USCG NVIC No. 8-87]

Table 3-8 High Strength Stiffener with Sandwich Side Shell

Item	b	h	A = b x h	d	Ad	Ad^2	i_o
A1	3.70	0.50	3.29*	7.25	23.85	172.93	0.069
A2	3.80	0.50	1.90	6.75	12.83	86.57	0.040
B	0.50	5.00	2.50	4.00	10.00	40.00	5.208
B	0.50	5.00	2.50	4.00	10.00	40.00	5.208
C	2.00	0.50	1.00	1.75	1.75	3.06	0.021
C	2.00	0.50	1.00	1.75	0.75	0.56	0.021
D	3.00	0.50	0.75	0.67	0.50	0.33	0.01
E1	28.94	0.25	7.23	1.37	9.95	13.68	0.038
E2	28.94	0.25	7.23	0.12	0.90	0.11	0.038
	Totals:		27.40		70.53	357.24	10.65

$$d_{NA} = \frac{\sum Ad}{\sum A} = \frac{70.53}{27.40} = 2.57 \text{ inches} \quad (3\text{-}91)$$

$$I_{NA} = \sum i_o + \sum Ad^2 - [\ Ad^2\ ] = 10.65 + 357.24 - [27.40 \text{ x } (2.57)^2] = 186.92 \quad (3\text{-}92)$$

$$SM_{top} = \frac{I}{d_{NA\ top}} = \frac{186.92}{4.93} = 37.9 \text{ in}^3 \quad (3\text{-}93)$$

$$SM_{bottom} = \frac{I}{d_{NA\ bottom}} = \frac{186.92}{2.57} = 72.73 \text{ in}^3 \quad (3\text{-}94)$$

SYMBOLS:

b = width or horizontal dimension

h = height or vertical dimension

d = height to center of A from reference axis

NA = neutral axis

i_o = item moment of inertia = $bh^3/12$

d_{NA} = distance from reference axis to real NA

I_{NA} = moment of inertia of stiffener and plate about the real neutral axis

The assumed neutral axis is at the outer shell so all distances are positive.

Note how the stiffened plate is divided into discreet areas and lettered.

Items *B* and *C* have the same effect on section properties and are counted twice.

Some simplifications were made for the vertical legs of the stiffener, item *B*. The item i_o was calculated using the equation for the *I* of an inclined rectangle. Considering the legs as vertical members would be a further simplification.

Item *D* is combined from both sides of the required bonding angle taper.

Ratio of elastic moduli $E = \frac{E_{Kevlar^®}}{E_{E-glass}} = \frac{9.8 \text{ msi}}{5.5 \text{ msi}}$

* Effective area of Kevlar® compared to the E-glass = 3.7 x 0.5 x 1.78 = 3.29

The overall required section modulus for this example must also reflect the mixed materials calculated as a modifier to the required section modulus:

$$SM_{Kevlar^®} = SM_{E-glass} \times \frac{E_{Kevlar^®}}{E_{E-glass}} \times \frac{Ultimate\ Strength_{E-glass}}{Ultimate\ Strength_{Kevlar^®}}$$

$$\frac{E_{Kevlar^®}}{E_{E-glass}} \times \frac{Ultimate\ Strength_{E-glass}}{Ultimate\ Strength_{Kevlar^®}} = \frac{9.8 \text{ msi}}{5.5 \text{ msi}} \times \frac{110 \text{ ksi}}{196 \text{ ksi}} = 1.0$$

Reinforcing fibers of different strengths and different moduli can be limited in the amount of strength that the fibers can develop by the maximum elongation tolerated by the resin and the strain to failure of the surrounding laminate. Therefore, the strength of the overall laminate should be analyzed, and for marginal safety factor designs or arrangements meeting the minimum of a rule, tests of a sample laminate should be conducted to prove the integrity of the design. In this example, the required section modulus was unchanged but the credit for the actual section modulus to meet the rule was significant.

Stress Concentrations

Stress concentrations from out-of-plane point loads occur for a variety of reasons. The largest loads on a boat often occur when the boat is in dry storage, transported over land, removed from the water or placed into the water. The weight of a boat is distributed over the hull while the boat is in the water, but is concentrated at support points of relatively small area when the boat is out of the water. As an example, an 80 foot long 18 foot wide power boat weighing 130,000 pounds would probably experience a hydrostatic pressure of only a few psi. If the boat was supported on land by 12 blocks with a surface area of 200 square inches each, the support areas would see an average load of 54 psi. Equipment mounting, such as rudders, struts, engines, mast and rigging, booms, cranes, etc. can also introduce out-of-plane point loads into the structure through mechanical fasteners.

Hauling and Blocking Stresses

When a vessel is hauled and blocked for storage, the weight of the vessel is not uniformly supported as in the water. The point loading from slings and cradle fixtures is obviously a problem. The overall hull, however, will be subject to bending stresses when a vessel is lifted with slings at two points. Except in extreme situations, in-service design criteria for small craft up to about 100 feet should be more severe than this case. When undergoing long term storage or over-land transit, consideration must be given to what fixtures will be employed over a given period of time. Creep behavior described in Chapter Six will dictate long-term structural response, especially under elevated temperature conditions. Large unsupported weights, such as machinery, keels or tanks, can produce unacceptable overall bending moments in addition to the local stress concentrations. During transportation, acceleration forces transmitted through the trailer's support system can be quite high. The onset of fatigue damage may be quite precipitous, especially with cored construction.

Engine Beds

If properly fabricated, engine beds in FRP vessels can potentially reduce the transmission of machinery vibration to the hull. Any foundation supporting propulsion machinery should be given the same attention afforded the main engine girders.

As a general rule, engine girders should be of sufficient strength, stiffness and stability to ensure proper operation of rotating machinery. Proper bonding to the hull over a large area is essential. Girders should be continuous through transverse frames and terminate with a gradual taper. Laminated timbers have been used as a core material because of excellent damping properties and the ability to hold lag bolt fasteners. Consideration should be given to bedding lag bolts in resin to prevent water egress. Some builders include some metallic stock between the core and the laminate to accept machine screws. If this is done, proper care should be exercised to guarantee that the metal remains bonded to the core. New, high density PVC foam cores offer an attractive alternative that eliminates the concern over future wood decay.

Hardware

Through-bolts are always more desirable than self-tapping fasteners. Hardware installations in single skin laminates is fairly straightforward. Backing plates of aluminum or stainless steel are always preferable over simple washers. If using only oversized washers, the local thickness should be increased by at least 25%. [3-23] The strength of hardware installations should be consistent with the combined load on a particular piece of hardware. In addition to shear and normal loads, applied moments with tall hardware must be considered. Winches that are mounted on pedestals are examples of hardware that produce large overturning moments.

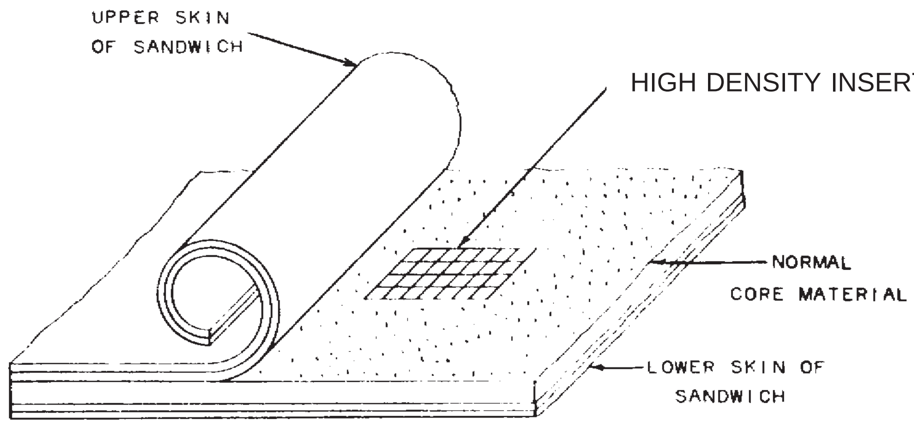


Figure 3-82 High Density Insert for Threaded or Bolted fasteners in Sandwich Construction [Gibbs and Cox, *Marine Design Manual for FRP*]

Hardware installation in cored construction requires a little more planning and effort. Low density cores have very poor holding power with screws and tend to compress under the load of bolts. Some builders simply taper the laminate to a solid thickness in way of planned hardware installations. This technique has the drawback of generally reducing the section modulus of the deck unless a lot of solid glass is used. A more efficient approach involves the insertion of a higher density core in way of planned hardware. In the past, the material of choice was plywood, but high density PVC foam will provide superior adhesion. Figure 3-82 illustrates this technique.

Hardware must often be located and mounted after the primary laminate is complete. To eliminate the possibility of core crushing, a compression tube as illustrated in Figure 3-83 should be inserted.

Nonessential hardware and trim, especially on small boats, is often mounted with screw fasteners. Table 3-9 is reproduced to provide some guidance in determining the potential holding force of these fasteners [3-24]. This table is suitable for use with mat and woven roving type laminate with tensile strength between 6 and 25 ksi; compressive strength between 10 and 22 ksi; and shear strength between 10 and 13 ksi.

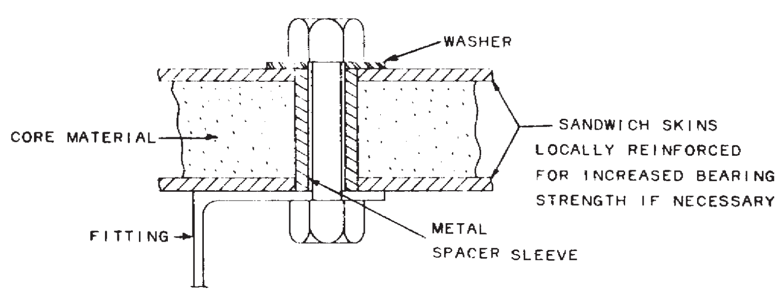


Figure 3-83 Through Bolting in Sandwich Construction [Gibbs and Cox, *Marine Design Manual for FRP*]

Table 3-9 Holding Forces of Fasteners in Mat/Polyester Laminates [Gibbs and Cox, Marine Design Manual for FRP]

Thread Size	Axial Holding Force				Lateral Holding Force			
	Minimum		Maximum		Minimum		Maximum	
	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)	Depth (ins)	Force (lbs)
Machine Screws								
4 - 40	.1250	40	.3125	450	.0625	150	.1250	290
6 - 32	.1250	60	.3750	600	.0625	180	.1250	380
8 - 32	.1250	100	.4375	1150	.0625	220	.1875	750
10 - 32	.1250	150	.5000	1500	.1250	560	.2500	1350
1/4 - 20	.1875	300	.6250	2300	.1875	1300	.3125	1900
5/16 - 18	.1875	400	.7500	3600	.1875	1600	.4375	2900
3/8 - 16	.2500	530	.8750	5000	.2500	2600	.6250	4000
7/16 - 14	.2500	580	1.0000	6500	.3125	3800	.7500	5000
1/2 - 13	.2500	620	1.1250	8300	.3750	5500	.8750	6000
9/16 - 12	.2500	650	1.2500	10000	.4375	6500	.9375	8000
5/8 - 11	.2500	680	1.3750	12000	.4375	6800	1.0000	11000
3/4 - 10	.2500	700	1.5000	13500	.4375	7000	1.0625	17000
Self-Tapping Thread Cutting Screws								
4 - 40	.1250	80	.4375	900	.1250	250	.1875	410
6 - 32	.1250	100	.4375	1100	.1250	300	.2500	700
8 - 32	.2500	350	.7500	2300	.1875	580	.3750	1300
10 - 32	.2500	400	.7500	2500	.1875	720	.4375	1750
1/4 - 20	.3750	600	1.0625	4100	.2500	1600	.6250	3200
Self-Tapping Thread Forming Screws								
4 - 24	.1250	50	.3750	500	.1250	220	.1875	500
6 - 20	.1875	110	.6250	850	.1250	250	.2500	600
8 - 18	.2500	180	.8125	1200	.1875	380	.3125	850
10 - 16	.2500	220	.9375	2100	.2500	600	.5000	1500
14 - 14	.3125	360	1.0625	3200	.2500	900	.6875	2800
5/16 - 18	.3750	570	1.1250	4500	.3125	1800	.8125	4400
3/8 - 12	.3750	700	1.1250	5500	.3750	3600	1.0000	6800

Sandwich Panel Testing

Background

Finite element models can be used to calculate panel deflections for various laminates under worst case loads [3-25,3-26], but the accuracy of these predictions is highly dependent on test data for the laminates. Traditional test methods [3-27] involve testing narrow strips, using ASTM standards outlined in Chapter Four. Use of these tests assumes that hull panels can be accurately modeled as a beam, thus ignoring the membrane effect, which is particularly important in sandwich panels [3-28]. The traditional tests also cause much higher stresses in the core, thus leading to premature failure [3-29].

A student project at the Florida Institute of Technology investigated three point bending failure stress levels for sandwich panels of various laminates and span to width ratios. The results were fairly consistent for biaxial (0°, 90°) laminates, but considerable variation in deflection and failure stress for double bias (±45°) laminates was observed as the aspect ratio was changed. Thus while the traditional tests yield consistent results for biaxial laminates, the test properties may be significantly lower than actual properties, and test results for double bias and triaxial laminates are generally inaccurate.

Riley and Isley [3-30] addressed these problems by using a new test procedure. They pressure loaded sandwich panels, which were clamped to a rigid frame. Different panel aspect ratios were investigated for both biaxial and double bias sandwich laminates. The results showed that the double bias laminates were favored for aspect ratios less than two, while biaxial laminates performed better with aspect ratios greater than three. Finite element models of these tests indicated similar results, however, the magnitude of the deflections and the pressure at failure was quite different. This was probably due to the method of fastening the edge of the panel. The method of clamping of the edges probably caused local stress concentrations and could not be modeled by either pinned- or fixed-end conditions.

Pressure Table Design

The basic concept of pressure loading test panels is sound, however, the edges or boundary conditions need to be examined closely. In an actual hull, a continuous outer skin is supported by longitudinal and transverse framing, which defines the hull panels. The appropriate panel boundary condition is one which reflects the continuous nature of the outer skin, while providing for the added stiffness and strength of the frames. One possible solution to this problem is to include the frame with the panel, and restrain the panel from the frame, rather than the panel edges. Also, extending the panel beyond the frame can approximate the continuous nature of the outer skin.

A test apparatus, consisting of a table, a water bladder for pressurizing the panel, a frame to constrain the sides of the water bladder, and framing to restrain the test panel, was developed and is shown in Figure 3-84. The test panel is loaded on the “outside,” while it is restrained by means of the integral frame system. The pressurization system can be operated either manually or under computer control, for pressure loading to failure or for pressure cycling to study fatigue.

Test Results

Sandwich laminates using four different reinforcements and three aspect ratios were constructed for testing. All panels used non-woven E-glass, vinyl ester resin and cross-linked

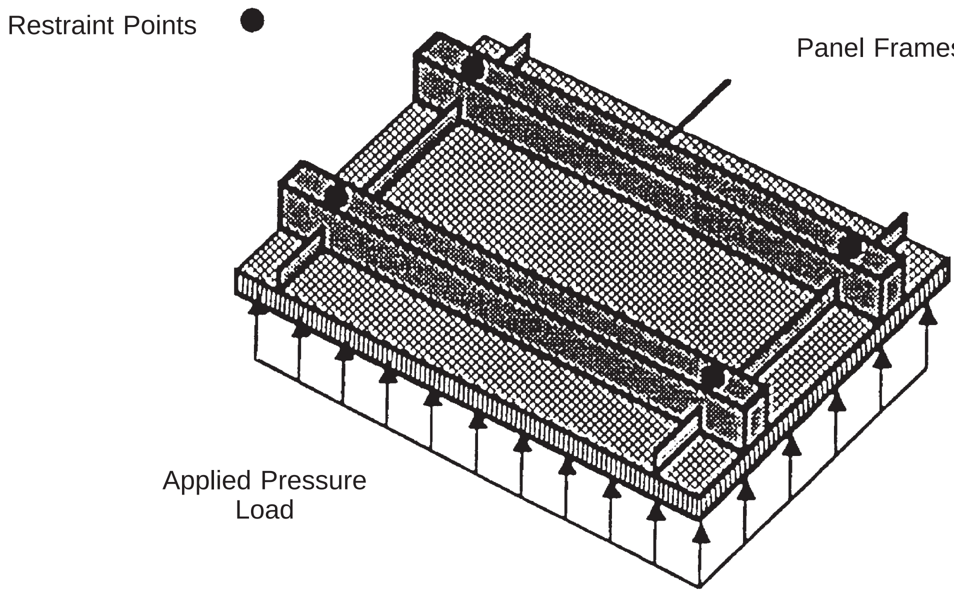


Figure 3-84 Schematic Diagram of Panel Testing Pressure Table [Reichard]

PVC foam cores over fir frames and stringers. The panels were loaded slowly (approximately 1 psi per minute) until failure.

MSC/NASTRAN, a finite element structural analysis program, was used to model the panel tests. The models were run using two different boundary conditions, pinned edges and fixed edges. The predicted deflections for fixed- and pinned-edge conditions along with measured results are shown in Figure 3-85.

The pinned-edge predictions most closely model the test results. Other conclusions that can be made as a result of early pressure table testing include:

- Quasi-isotropic laminates are favored for square panels.
- Triaxial laminates are favored for panels of aspect ratios greater than two.

Deflection increase with aspect ratio until asymptotic values are obtained. Asymptotic values of deflection are reached at aspect ratios between 2.0 and 3.5.

The pressure table test method provides strength and stiffness data for the panel structure but does not provide information about specific material properties. Therefore, the test is best suited for comparing candidate structures.

Testing of Structural Grillage Systems

Figure 3-86 shows a hat-stiffened panel subjected to in-plane and out-of-plane loads tested at the U.S. Naval Academy. The structure modeled would be typical of a longitudinally stiffened hull panel. Note the half-sine wave pattern of the collapsed skin even as the panel was subjected to out-of-plane loads from the water bladder with nominal loading. After the panel separated from the stiffeners, the hat sections experienced shear failure.

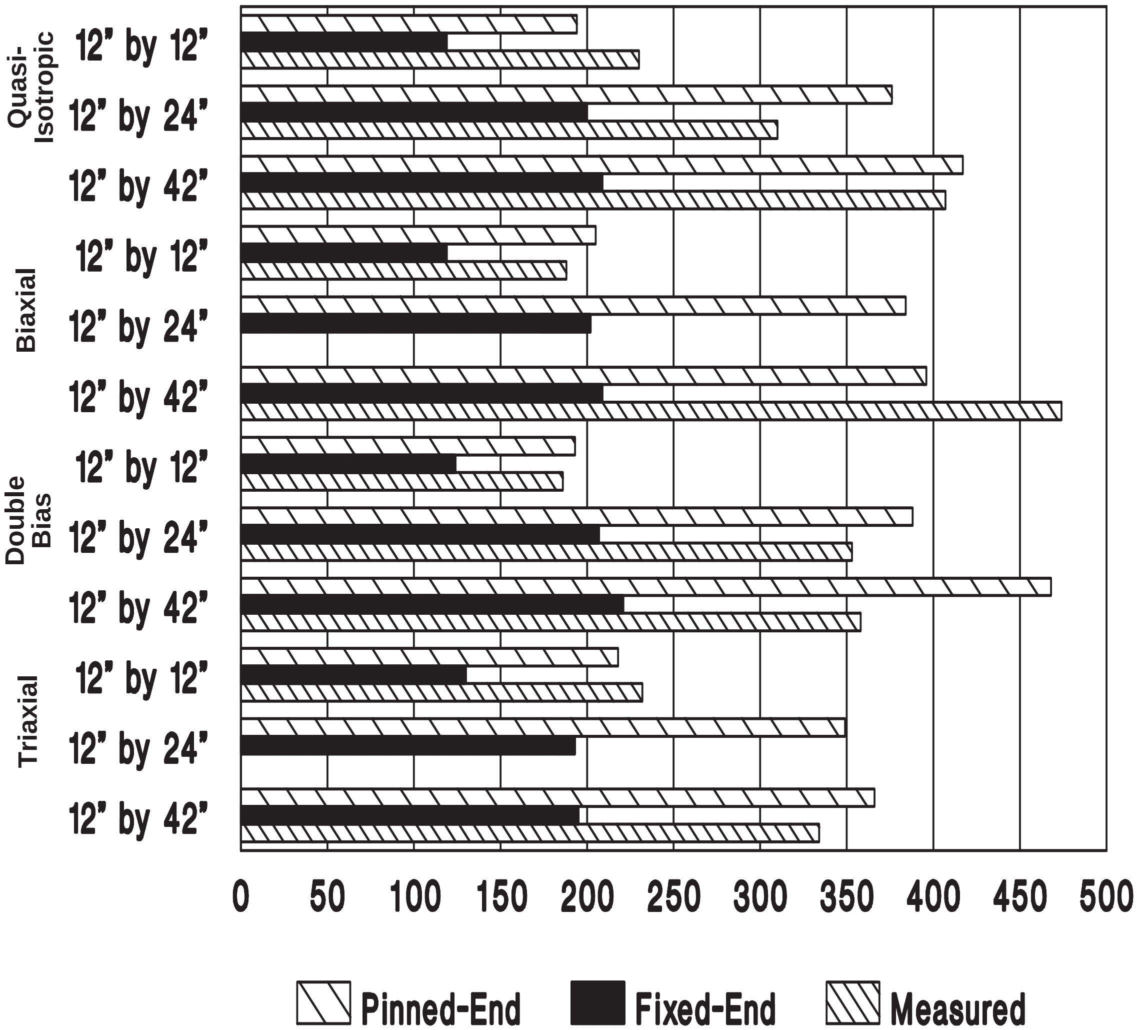


Figure 3-85 Computed and Measured Deflections (mils) of PVC Foam Core Panels Subjected to a 10 psi Load [from Reichard, Ronnal P., "Pressure Panel Testing of GRP Sandwich Panels,", MACM' 92 Conference, Melbourne, FL, March 24-26, 1992.

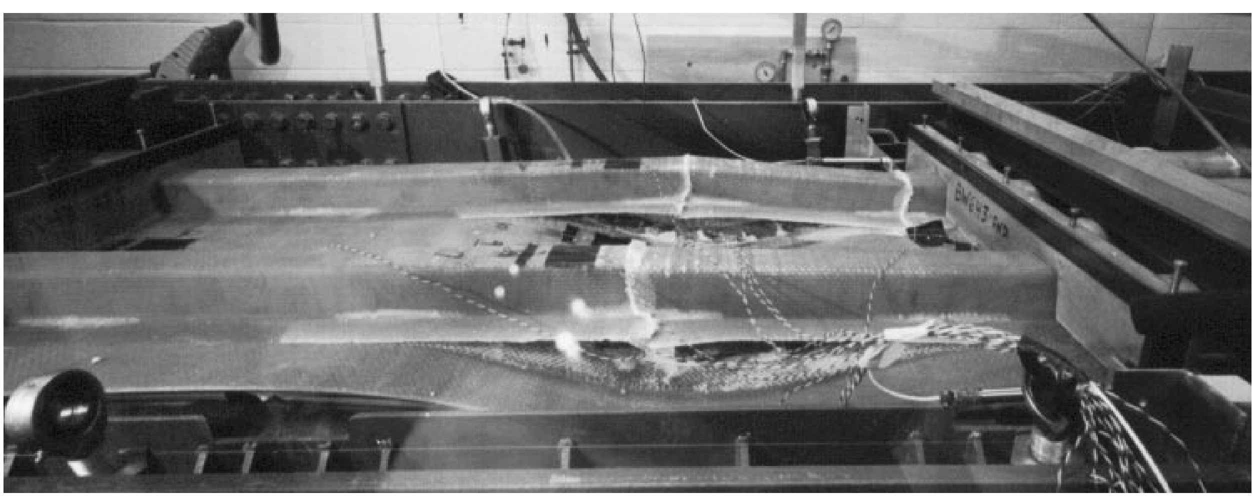


Figure 3-86 Hat-Stiffened Panel Tested to Failure at the U.S. Naval Academy

Hydromat Test System (HTS)

Bill Bertelsen of Gougeon Brothers and Dave Sikarskie of Michigan Technological University have developed a two dimensional panel testing device and governing design equations. The test device, shown in Figure 3-87, subjects panels to out-of-plane loads with simply-supported end conditions. The boundary conditions have been extended to cover sandwich panels with soft cores, thereby enabling characterization of sandwich panels both elastically and at failure. A methodology has been developed for obtaining numerical and experimental values for bending and core shear rigidities, which both contribute to measured deflections.

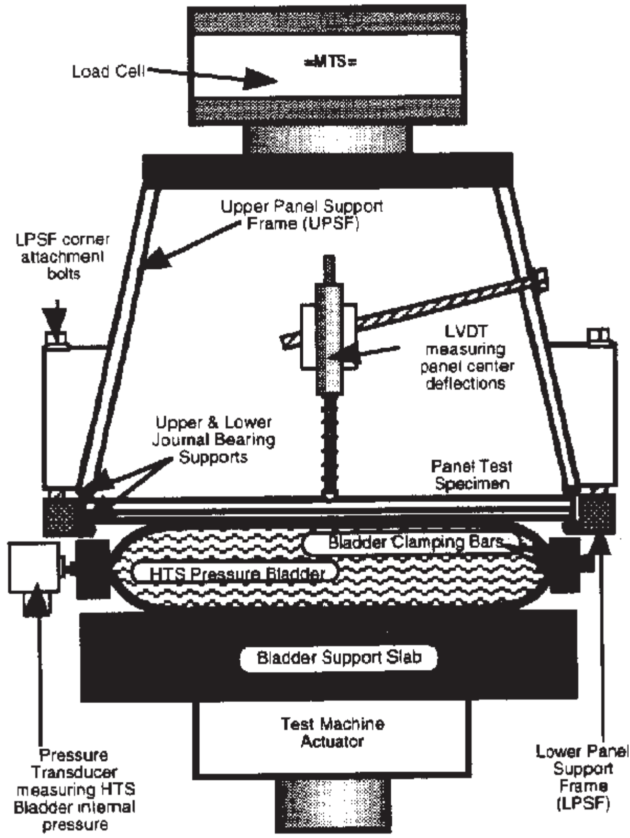


Figure 3-87 Schematic Diagram of the Hydromat Test System [Bertlesen & Sikarskie]

In the simplest form, the deflection, δ, is given as:

$$\delta = \frac{c_1}{B} + \frac{c_2}{S} \qquad (3\text{-}95)$$

where:

c_1& c_2 = constants

B = bending stiffness

S = core shear stiffness

Tests were run on panels with varying stiffness to verify the methodology. Table 3-10 summarizes some results, showing the close agreement between experimental and theoretical overall bending and core shear stiffness.

Table 3-10 Summary of Experimental and Theoretical Bending and Shear Stiffness [Bertlesen, Eyre and Sikarskie, *Verification of HTS for Sandwich Panels*]

Panel	Bladder Pressure (kPa)	Total HTS Deflection	$(\varepsilon_x + \varepsilon_y)$ Exp. μ strain	B, exp (10^4 nM)	B, theory (10^4 nM)	S, exp (10^4 nM)	S, theory (10^4 nM)
1	31.0	2.78	463	2.08	2.52	3.48	3.72
2	48.3	2.85	719	2.12	2.55	6.43	5.24
3	75.8	2.49	1062	2.33	2.43	17.68	17.04

Fatigue

A fundamental problem concerning the engineering uses of fiber reinforced plastics (FRP) is the determination of their resistance to combined states of cyclic stress. [4-1] Composite materials exhibit very complex failure mechanisms under static and fatigue loading because of anisotropic characteristics in their strength and stiffness. [4-2] Fatigue causes extensive damage throughout the specimen volume, leading to failure from general degradation of the material instead of a predominant single crack. A predominant single crack is the most common failure mechanism in static loading of isotropic, brittle materials such as metals. There are four basic failure mechanisms in composite materials as a result of fatigue: matrix cracking, delamination, fiber breakage and interfacial debonding. The different failure modes combined with the inherent anisotropies, complex stress fields, and overall non-linear behavior of composites severely limit our ability to understand the true nature of fatigue. [4-3] Figure 4-1 shows a typical comparison of the fatigue damage of composites and metals over time.

Many aspects of tension-tension and tension-compression fatigue loading have been investigated, such as the effects of heat, frequency, pre-stressing samples, flawing samples, and moisture [4-5 through 4-13]. Mixed views exist as to the effects of these parameters on composite laminates, due to the variation of materials, fiber orientations, and stacking sequences, which make each composite behave differently.

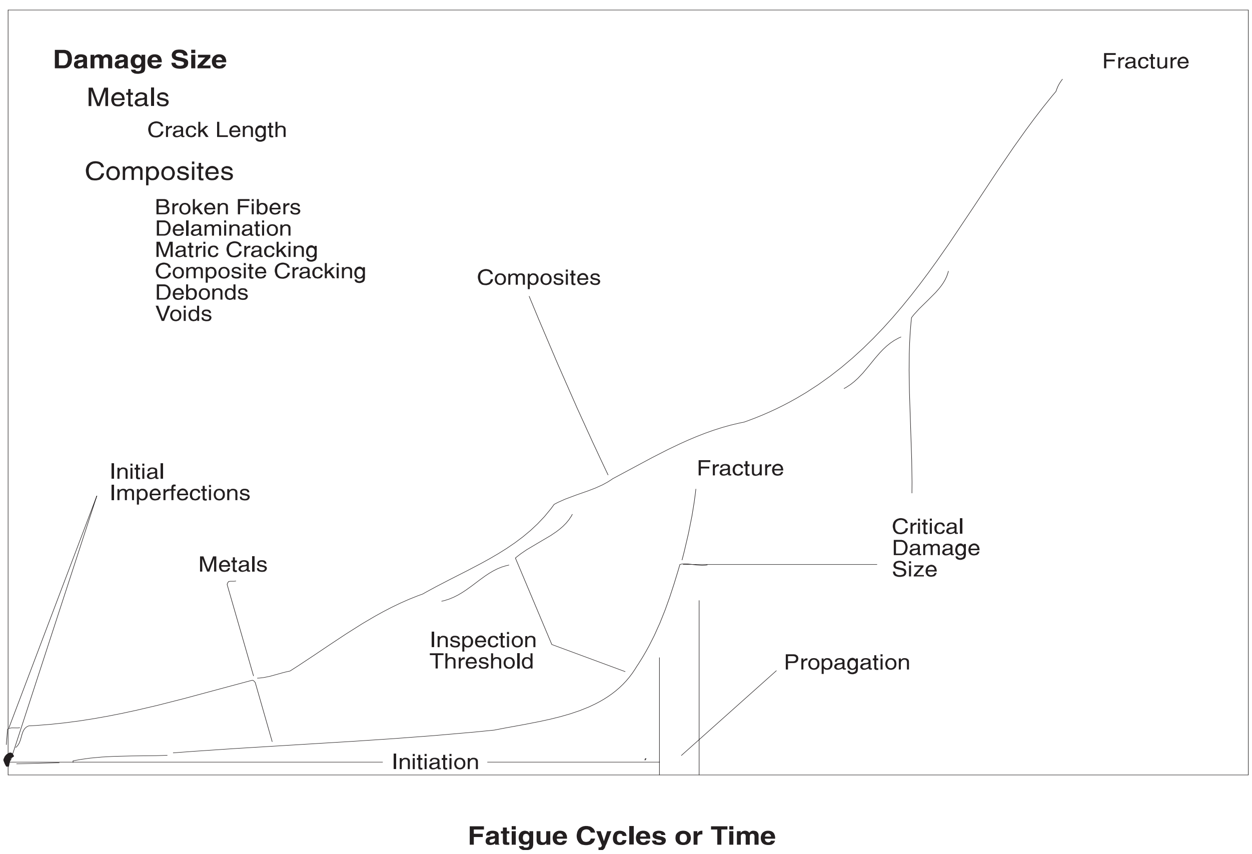


Figure 4-1 Typical Comparison of Metal and Composite Fatigue Damage [Salkind, *Fatigue of Composites*]

Extensive work has been done to establish failure criteria of composites during fatigue loading [4-1, 4-5, 4-14, 4-15]. Fatigue failure can be defined either as a loss of adequate stiffness, or as a loss of adequate strength. There are two approaches to determine fatigue life; constant stress cycling until loss of strength, and constant amplitude cycling until loss of stiffness. The approach to utilize depends on the design requirements for the laminate.

In general, stiffness reduction is an acceptable failure criterion for many components which incorporate composite materials. [4-15] Figure 4-2 shows a typical curve of stiffness reduction for composites and metals. Stiffness change is a precise, easily measured and easily interpreted indicator of damage, which can be directly related to microscopic degradation of composite materials. [4-15]

In a constant amplitude deflection loading situation the degradation rate is related to the stress within the composite sample. Initially, a larger load is required to deflect the sample. This corresponds to a higher stress level. As fatiguing continues, less load is required to deflect the sample, hence a lower stress level can exist in the sample. As the stress within the sample is reduced, the amount of deterioration in the sample decreases. The reduction in load required to deflect the sample corresponds to a reduction in the stiffness of that sample. Therefore, in constant amplitude fatigue, the stiffness reduction is dramatic at first, as substantial matrix degradation occurs, and then quickly tapers off until only small reductions occur.

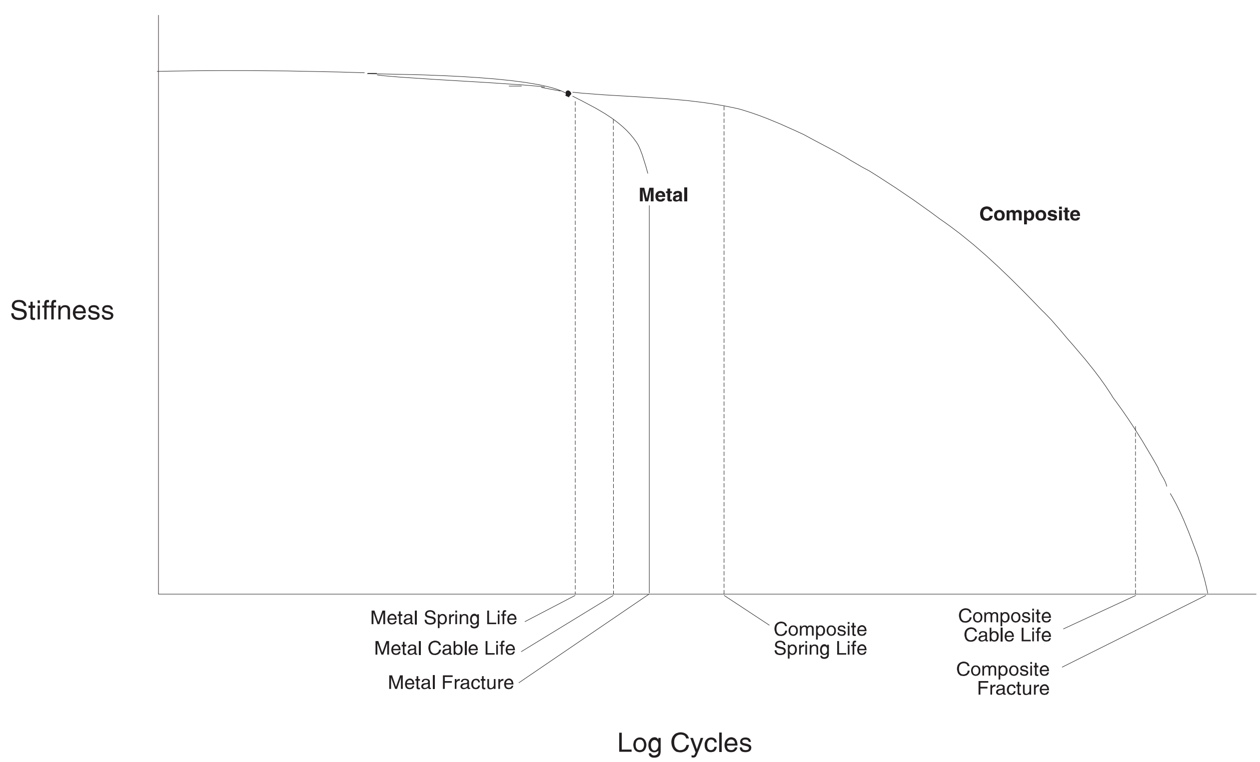


Figure 4-2 Comparison of Metal and Composite Stiffness Reduction [Salkind, *Fatigue of Composites*]

In a unidirectional fiber composite, cracks may occur along the fiber axis, which usually involves matrix cracking. Cracks may also form transverse to the fiber direction, which usually indicates fiber breakage and matrix failure. The accumulation of cracks transverse to fiber direction leads to a reduction of load carrying capacity of the laminate and with further fatigue cycling may lead to a jagged, irregular failure of the composite material. This failure mode is drastically different from the metal fatigue failure mode, which consists of the initiation and propagation of a single crack. [4-1] Hahn [4-16] predicted that cracks in composite materials propagate in four distinct modes. These modes are illustrated in Figure 4-3, where region I corresponds to the fiber and region II corresponds to the matrix.

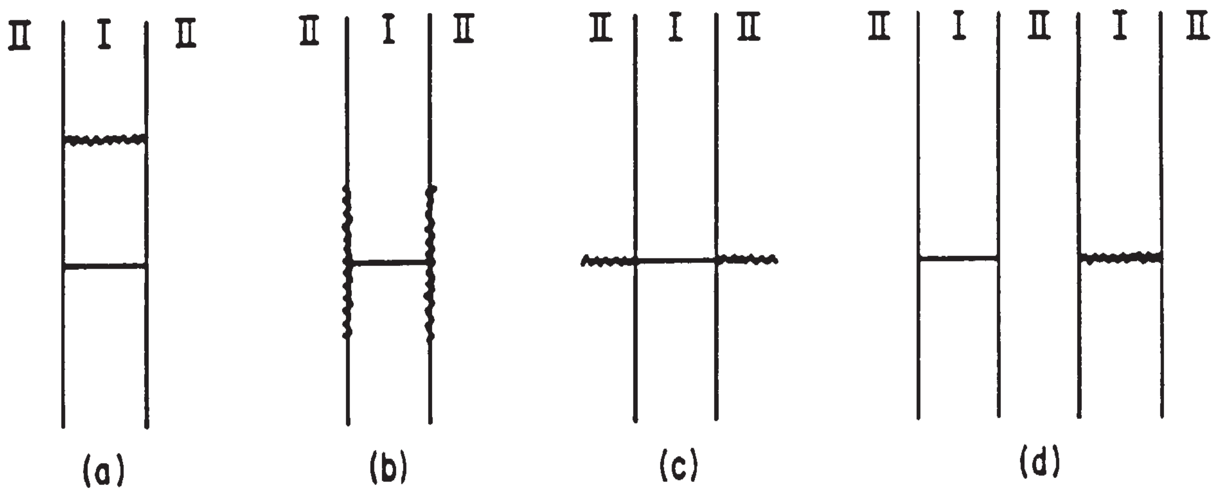


Figure 4-3 Fatigue Failure Modes for Composite Materials - **Mode (a)** represents a tough matrix where the crack is forced to propagate through the fiber. **Mode (b)** occurs when the fiber/matrix interface is weak. This is, in effect, debonding. **Mode (c)** results when the matrix is weak and has relatively little toughness. Finally, **Mode (d)** occurs with a strong fiber/matrix interface and a tough matrix. Here, the stress concentration is large enough to cause a crack to form in a neighboring fiber without cracking of the matrix. **Mode (b)** is not desirable because the laminate acts like a dry fiber bundle and the potential strength of the fibers is not realized. **Mode (c)** is also undesirable because it is similar to crack propagation in brittle materials. The optimum strength is realized in **Mode (a),** as the fiber strengths are fully utilized. [Hahn, *Fatigue of Composites*]

Minor cracks in composite materials may occur suddenly without warning and then propagate at once through the specimen. [4-1] It should be noted that even when many cracks have been formed in the resin, composite materials may still retain respectable strength properties. [4-17] The retention of these strength properties is due to the fact that each fiber in the laminate is a load-carrying member and once a fiber fails the load is redistributed to another fiber.

Composite Fatigue Theory

There are many theories used to describe composite material strength and fatigue life. Since no one analytical model can account for all the possible failure processes in a composite material, statistical methods to describe fatigue life have been adopted. Weibull distribution has proven to be a useful method to describe the material strength and fatigue life. Weibull distribution is based on three parameters; scale, shape and location. Estimating these parameters is based on one of three methods: the maximum likelihood estimation method, the moment estimation method, or the standardized variable method. These methods of estimation are discussed in detail in references [4-18, 4-19]. It has been shown that the moment estimation method and the maximum-likelihood method lead to large errors in estimating the scale and the shape parameters, if the location parameter is taken to be zero. The standardized variable estimation gives accurate and more efficient estimates of all three parameters for low shape boundaries. [4-19]

Another method used to describe fatigue behavior is to extend static strength theory to fatigue strength by replacing static strengths with fatigue functions.

The power law has been used to represent fatigue data for metals when high numbers of cycles are involved. By adding another term into the equation for the ratio of oscillatory-to-mean stress, the power law can be applied to composite materials. [4-20]

Algebraic and linear first-order differential equations can also be used to describe composite fatigue behavior. [4-14]

There are many different theories used to describe fatigue life of composite materials. However, given the broad range of usage and diverse variety of composites in use in the marine industry, theoretical calculations as to the fatigue life of a given composite should only be used as a first-order indicator. Fatigue testing of laminates in an experimental test program is probably the best method of determining the fatigue properties of a candidate laminate. Further testing and development of these theories must be accomplished to enhance their accuracy. Despite the lack of knowledge, empirical data suggest that composite materials perform better than some metals in fatigue situations. Figure 4-4 depicts fatigue strength characteristics for some metal and composite materials. [4-21]

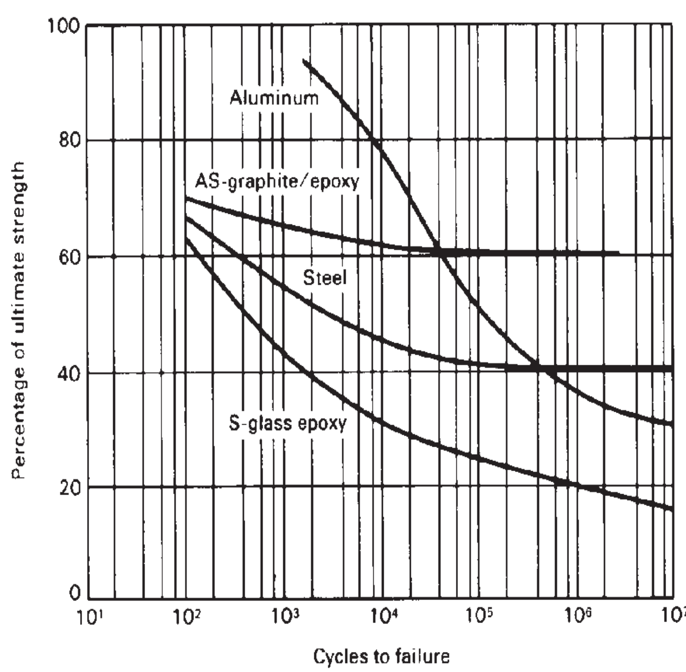


Figure 4-4 Comparison of Fatigue Strengths of Graphite/Epoxy, Steel, Fiberglass/Epoxy and Aluminum [Hercules]

Fatigue Test Data

Although precise predictions of fatigue life expectancies for FRP laminates is currently beyond the state-of-the-art of analytical techniques, some insight into the relative performance of constituent materials can be gained from published test data. The Interplastic Corporation conducted an exhaustive series of fatigue tests on mat/woven roving laminates to compare various polyester and vinyl ester resin formulations. [4-22] The conclusion of those tests is shown in Figure 4-5 and is summarized as follows:

> "Cyclic flexural testing of specific polyester resin types resulted in predictable data that oriented themselves by polymer description, i.e., orthophthalic was exceeded by isophthalic, and both were vastly exceeded by vinyl ester type resins. Little difference was observed between the standard vinyl ester and the new pre-accelerated thixotropic vinyl esters."

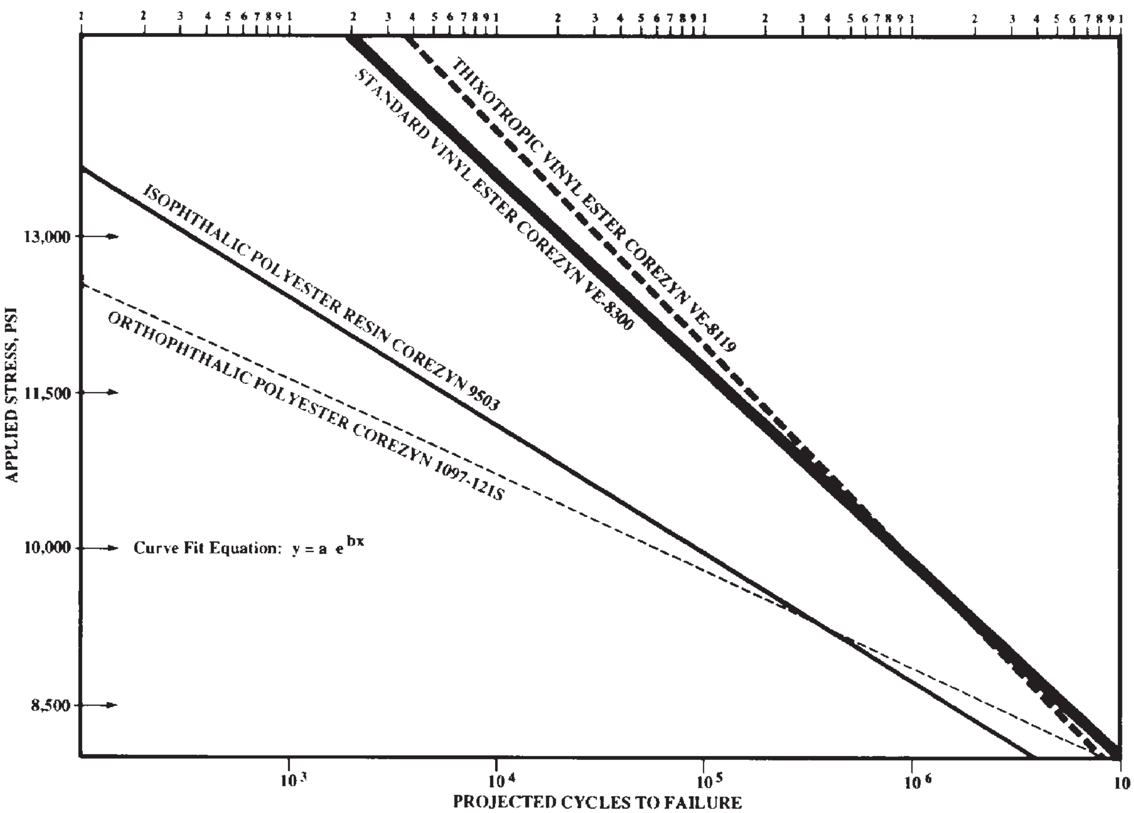


Figure 4-5 Curve Fit of ASTM D671 Data for Various Types of Unsaturated Polyester Resins [Interplastic, *Cycle Test Evaluation of Various Polyester Types and a Mathematical Model for Predicting Flexural Fatigue Endurance*]

With regards to reinforcement materials used in marine laminates, there is not a lot of comparative test data available to illustrate fatigue characteristics. It should be noted that fatigue performance is very dependent on the fiber/resin interface performance. Tests by various investigators [4-23] suggest that a ranking of materials from best to worst would look like:

- High Modulus Carbon Fiber;
- High Strength and Low Modulus Carbon;
- Kevlar®/Carbon Hybrid;
- Kevlar®;
- Glass/Kevlar® Hybrid;
- S-Glass; and
- E-Glass.

The construction and orientation of the reinforcement also plays a critical role in determining fatigue performance. It is generally perceived that larger quantities of thinner plies perform better than a few layers of thick plies. Figure 4-6 shows a comparison of various fabric constructions with regard to fatigue performance.

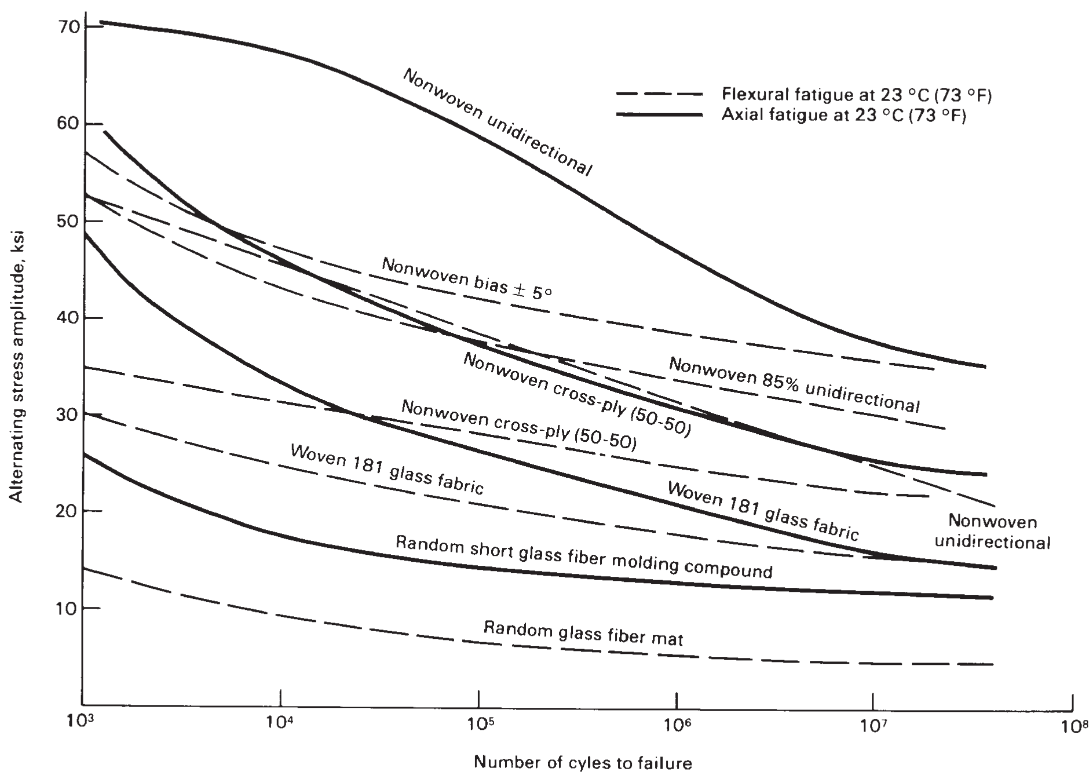


Figure 4-6 Comparative Fatigue Strengths of Nonwoven Unidirectional Glass Fiber Reinforced Plastic Laminates [*ASM Engineers' Guide to Composite Materials*]

Although some guidance has been provided to assist in the preliminary selection of materials to optimize fatigue performance, a thorough test program would be recommended for any large scale production effort that was fatigue performance dependent. This approach has been taken for components such as helicopter and wind turbine rotors, but is generally beyond the means of the average marine fabricator.

Impact

The introduction of FRP and FRP sandwich materials into the boating industry has led to lighter, stiffer and faster boats. This leads, in general, to reduced impact performance, since higher speeds cause impact energy to be higher, while stiffer structures usually absorb less impact energy before failure. Thus, the response of modern FRP composite marine structures to impact loads is an important consideration.

The complexity and variability of boat impacts makes it very difficult to define an impact load for design purposes. There is also a lack of information on the behavior of the FRP composite materials when subjected to the high load rates of an impact, and analytical methods are, at present, relatively crude. Thus, it is difficult to explicitly include impact loads into the structural analysis and design process. Instead, basic knowledge of the principles of impact loading and structural response is used as a guide to design structures with superior impact performance.

The impact response of a composite structure can be divided into four categories. In the first, the entire energy of the impact is absorbed by the structure in elastic deformation, and then released when the structure returns to its original position or shape. Higher energy levels exceed the ability of the structure to absorb the energy elastically. The next level is plastic deformation, in which some of the energy is absorbed by elastic deformation, while the remainder of the energy is absorbed through permanent plastic deformation of the structure. Higher energy levels result in energy absorbed through damage to the structure. Finally, the impact energy levels can exceed the capabilities of the structure, leading to catastrophic failure. The maximum energy which can be absorbed in elastic deformation depends on the stiffness of the materials and the geometry of the structure. Damage to the structural laminate can be in the form of resin cracking, delamination between plies, debonding of the resin fiber interface, and fiber breakage for solid FRP laminates, with the addition of debonding of skins from the core in sandwich laminates. The amount of energy which can be absorbed in a solid laminate and structural damage depends on the resin properties, fiber types, fabric types, fiber orientation, fabrication techniques and rate of impact.

Impact Design Considerations

The general principles of impact design are as follows. The kinetic energy of an impact is:

$$K.E. = \frac{m\,v^2}{2} \qquad (4\text{-}1)$$

where:

v = the collision velocity and m is the mass of the boat or the impactor, whichever is smaller.

The energy that can be absorbed by an isotropic beam point loaded at mid-span is:

$$K.E. = \int_0^L \frac{M^2}{2\,E\,I}\,ds \qquad (4\text{-}2)$$

where:

L = the span length

M = the moment

E = Young's Modulus

I = moment of inertia

For the small deformations of a composite panel, the expression can be simplified to:

$$K.E. = \frac{S^2 \ A L r^2}{6 E c^2} \tag{4-3}$$

where:

S = the stress

A = cross-sectional area

r = the depth of the beam

c = the distance from the neutral axis to the outermost fiber of the beam

From this relationship, the following conclusions can be drawn:

- Increasing the skin laminate modulus *E* causes the skin stress levels to increase. The weight remains the same and the flexural stiffness is increased.;
- Increasing the beam thickness *r* decreases the skin stress levels, but it also increases flexural stiffness and the weight; and
- Increasing the span length *L* decreases the skin stress levels. The weight remains the same, but flexural stiffness is decreased.

Therefore, increasing the span will decrease skin stress levels and increase impact energy absorption, but the flexural stiffness is reduced, thus increasing static load stress levels.

For a sandwich structure:

$$M = \frac{S I}{d} \tag{4-4}$$

$$I \approx \frac{b t d^2}{2} \tag{4-5}$$

where:

S = skin stress

d = core thickness

b = beam width

t = skin thickness

Thus the energy absorption of a sandwich beam is:

$$K.E. = \frac{S^2\ b\ t\ L}{4\ E} \quad (4\text{-}6)$$

From this relationship, the following conclusions can be drawn:

- Increasing the skin laminate modulus *E* causes the skin stress levels to increase. The weight remains the same and the flexural stiffness is increased.;
- Increasing the skin thickness *t* decreases the skin stress levels, but it also increases flexural stiffness and the weight;
- Increasing the span length *L* decreases the skin stress levels. The weight remains the same, but flexural stiffness is decreased; and
- Core thickness alone does not influence impact energy absorption.

Therefore, increasing the span will decrease skin stress levels and increase impact energy absorption, while the flexural stiffness can be maintained by increasing the core thickness.

An impact study investigating sandwich panels with different core materials, different fiber types and different resins supports some of the above conclusions. [4-24] This study found that panels with higher density foam cores performed better than identical panels with lower density foam cores, while rigid cores such as balsa and Nomex® did not fare as well as the foam. This indicates that strength is a more important property than modulus for impact performance of core materials. The difference in performance between panels constructed of E-glass, Kevlar®, and carbon fiber fabrics was small, with the carbon fiber panels performing slightly better than the other two types. The reason for these results is not clear, but the investigator felt that the higher flexural stiffness of the carbon fiber skin distributed the impact load over a greater area of the foam core, thus the core material damage was lower for this panel. Epoxy, polyester and vinyl ester resins were also compared. The differences in performance were slight, with the vinyl ester providing the best performance, followed by polyester and epoxy. Impact performance for the different resins followed the strength/stiffness ratio, with the best performance from the resin with the highest strength to stiffness ratio. General impact design concepts can be summarized as follows:

- Impact energy absorption mechanisms;
- Elastic deformation;
- Matrix cracking;
- Delamination;
- Fiber breakage;
- Interfacial debonding; and
- Core shear.

The failure mechanism is usually that of the limiting material in the composite, however, positive synergism between specific materials can dramatically improve impact performance. General material relationships are as follows:

- Kevlar® and S-glass are better than E-glass and carbon fibers;
- Vinyl ester is better than epoxy and polyester;
- Foam core is better than Nomex® and Balsa;
- Quasi-isotropic laminates are better than Orthotropic laminates.;
- Low fiber/resin ratios are better than high; and
- Many thin plies of reinforcing fabric are better than a few thicker plies.

Theoretical Developments

Theoretical and experimental analysis have been conducted for ballistic impact (high speed, small mass projectile) to evaluate specific impact events. The theory can be applied to lower velocity, larger mass impacts acting on marine structures as summarized in Figure 4-7 and below.

1. Determine the surface pressure and its distribution induced by the impactor as a function of impact parameters, laminate and structure properties, and impactor properties.

2. Determine the internal three dimensional stress field caused by the surface pressure.

3. Determine the failure modes of the laminate and structure resulting from the internal stresses, and how they interact to cause damage.

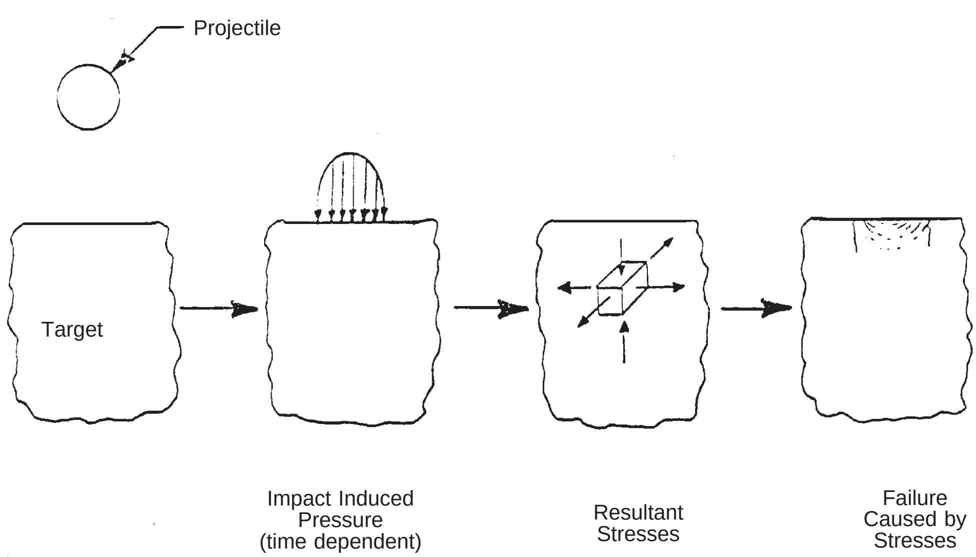


Figure 4-7 Impact Initiation and Propagation [Jones, *Impact Analysis of Composite Sandwich Panels as a Function of Skin, Core and Resin Materials*]

Delamination

Interlaminar stress in composite structures usually results from the mismatch of engineering properties between plies. These stresses are the underlying cause of delamination initiation and propagation. Delamination is defined as the cracking of the matrix between plies. The aforementioned stresses are out-of-plane and occur at structural discontinuities, as shown in Figure 4-8. In cases where the primary loading is in-plane, stress gradients can produce an out-of-plane load scenario because the local structure may be discontinuous.

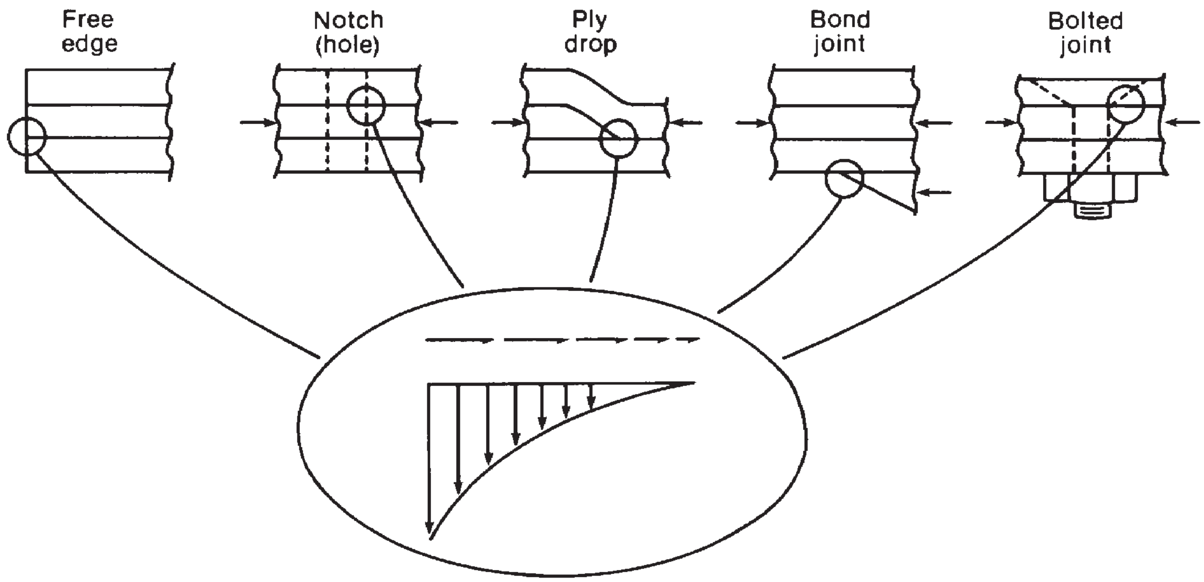


Figure 4-8 Sources of Out-of-Plane Loads from Load Path Discontinuities [ASM, *Engineered Materials Handbook*]

Analysis of the delamination problem has identified the strain energy release rate, *G*, as a key parameter for characterizing failures. This quantity is independent of lay-up sequence or delamination source. [4-25] NASA and Army investigators have shown from finite element analysis that once a delamination is modeled a few ply thicknesses from an edge, *G* reaches a plateau given by the equation shown in Figure 4-9.

where:

t = laminate thickness

ε = remote strain

E_{LAM} = modulus before delamination

E^* = modulus after delamination

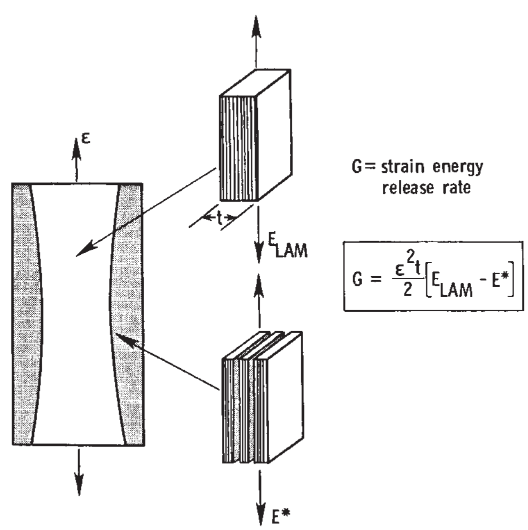


Figure 4-9 Strain Energy Release Rate for Delamination Growth [O'Brien, *Delamination Durability of Composite Materials for Rotorcraft*]

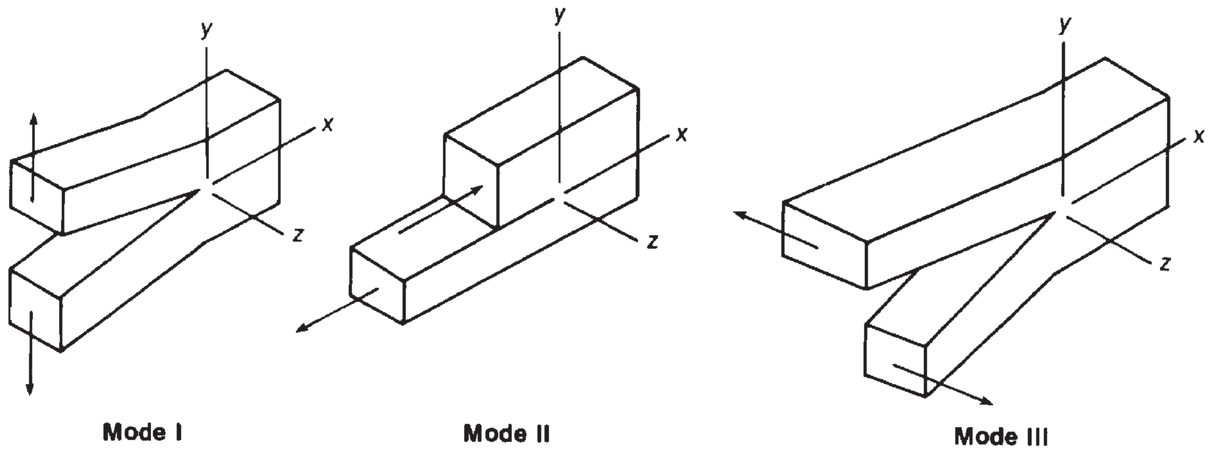


Figure 4-10 Basic Modes of Loading Involving Different Crack Surface Displacements [ASM, *Engineered Materials Handbook*]

Linear elastic fracture mechanics identifies three distinct loading modes that correspond to different crack surface displacements. Figure 4-10 depicts these different modes as follows:

- **Mode I** - Opening or tensile loading, where the crack surfaces move directly apart;
- **Mode II** - Sliding or in-plane shear, where the crack surfaces slide over each other in a direction perpendicular to the leading edge of the crack; and
- **Mode III** - Tearing or antiplane shear, where the crack surfaces move relative to each other and parallel to the leading edge of the crack (scissoring).

Mode I is the dominant form of loading in cracked metallic structures. With composites, any combination of modes may be encountered. Analysis of mode contribution to total strain energy release rate has been done using finite element techniques, but this method is too cumbersome for checking individual designs. A simplified technique has been developed by Georgia Tech for NASA/Army whereby Mode II and III strain energy release rates are calculated by higher order plate theory and then subtracted from the total G to determine Mode I contribution.

Delamination in tapered laminates is of particular interest because the designer usually has control over taper angles. Figure 4-11 shows delamination initiating in the region “A” where the first transition from thin to thick laminate occurs. This region is modeled as a flat laminate with a stiffness discontinuity in the outer “belt” plies and a continuous stiffness in the inner “core” plies. The belt stiffness in the tapered region E_2 was obtained from a tensor transformation of the thin region E_1 transformed through the taper angle beta. As seen in the figure's equation, G will increase as beta increases, because the belt stiffness is a function of the taper angle. [4-25]

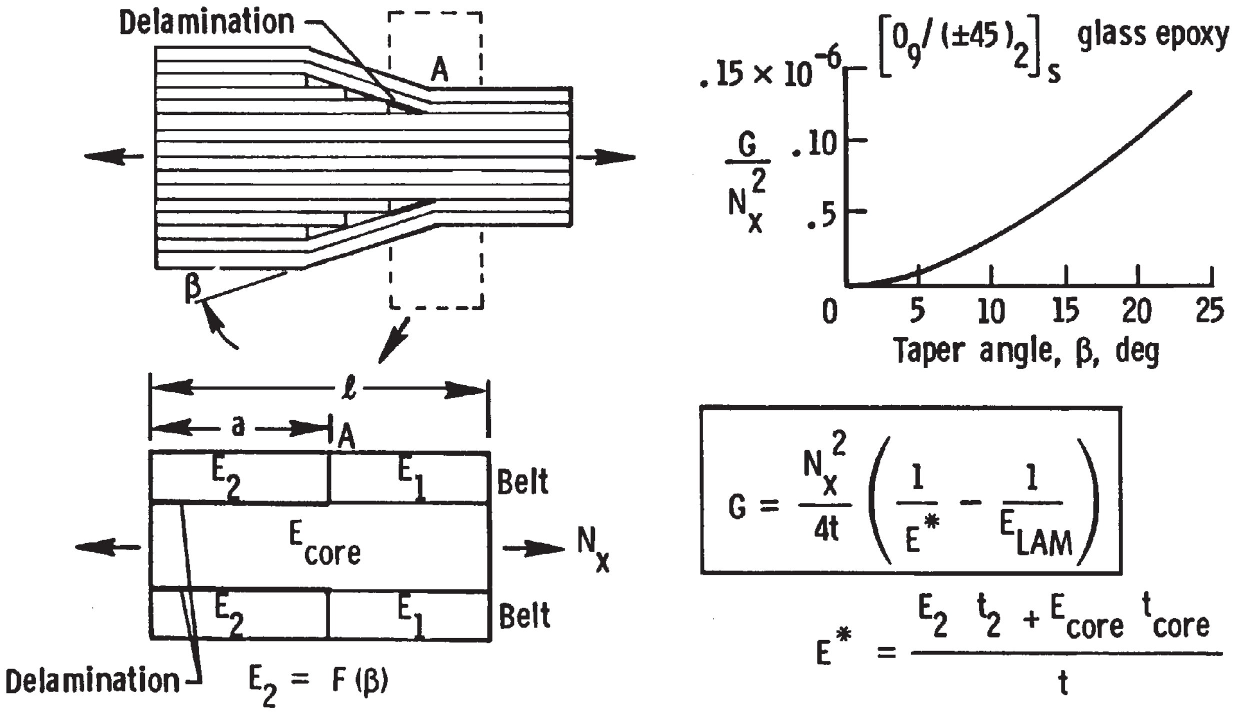


Figure 4-11 Strain Energy Release Rate Analysis of Delamination in a Tapered Laminate [O'Brien, *Delamination Durability of Composite Materials for Rotorcraft*]

Lately, there has been much interest in the aerospace industry in the development of "tough" resin systems that resist impact damage. The traditional, high-strength epoxy systems are typically characterized as brittle when compared to systems used in the marine industry. In a recent test of aerospace matrices, little difference in delamination durability showed up. However, the tough matrix composites did show slower delamination growth. Figure 4-12 is a schematic of a log-log plot of delamination growth rate, $^{da}/_{dN}$,

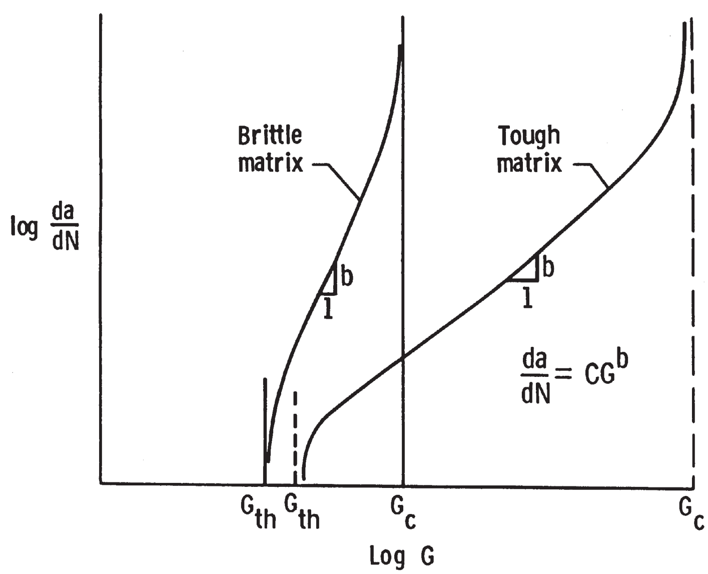


Figure 4-12 Comparison of Delamination Growth Rates for Composites with Brittle and Tough Matrices [O'Brien, *Delamination Durability of Composite Materials for Rotorcraft*]

where:

G_c = cyclic strain energy release rate

G_{th} = cyclic threshold

Water Absorption

When an organic matrix composite is exposed to a humid environment or liquid, both the moisture content and material temperature may change with time. These changes usually degrade the mechanical properties of the laminate. The study of water absorption within composites is based on the following parameters as a function of time: [4-26]

- The temperature inside the material as a function of position;
- The moisture concentration inside the material;
- The total amount (mass) of moisture inside the material;
- The moisture and temperature induced "hygrothermal" stress inside the material;
- The dimensional changes of the material; and
- The mechanical, chemical, thermal or electric changes.

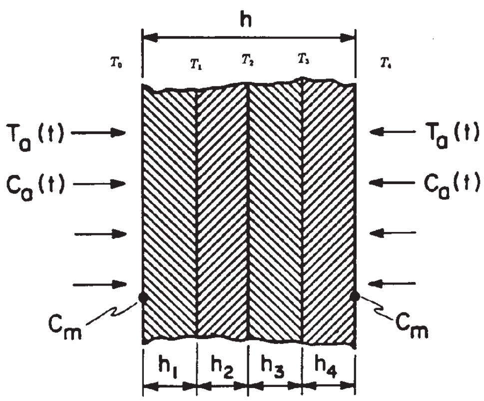


Figure 4-13 Time Varying Environmental Conditions in a Multilayered Composite [Springer, *Environmental Effects on Composite Materials*]

To determine the physical changes within a composite laminate, the temperature distribution and moisture content must be determined. When temperature varies across the thickness only and equilibrium is quickly achieved, the moisture and temperature distribution process is called "Fickian" diffusion, which is analogous to Fourier's equation for heat conduction. Figure 4-13 illustrates some of the key parameters used to describe the Fickian diffusion process in a multilayered composite. The letter *T* refers to temperature and the letter *C* refers to moisture concentration.

Fick's second law of diffusion can be represented in terms of three principal axes by the following differential equation: [4-27]

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2{}_x} + D_y \frac{\partial^2 c}{\partial x^2{}_y} + D_z \frac{\partial^2 c}{\partial x^2{}_z} \qquad (4\text{-}7)$$

Figure 4-14 shows the change in moisture content, *M*, versus the square root of time. The apparent plateau is characteristic of Fickian predictions, although experimental procedures have shown behavior that varies from this. Additional water absorption has been attributed to the relaxation of the polymer matrix under the influence of swelling stresses. [4-28] Figure 4-15 depicts some experimental results from investigations conducted at elevated temperatures.

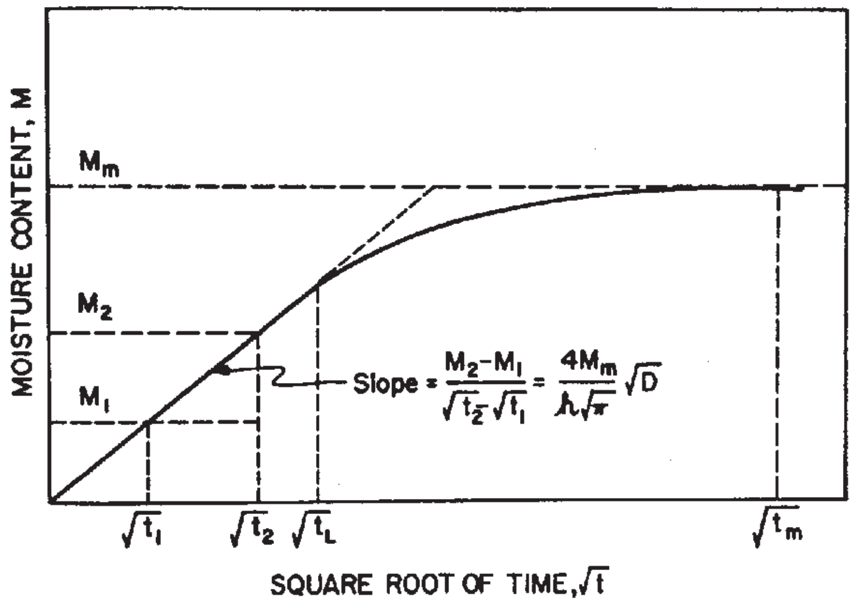


Figure 4-14 Laminate Water Absorbtion Kinetics for Experimental Laminate Specimens [Pritchard, *The Use of Water Absorbtion Kinetic Data to Predict Laminate Property Changes*]

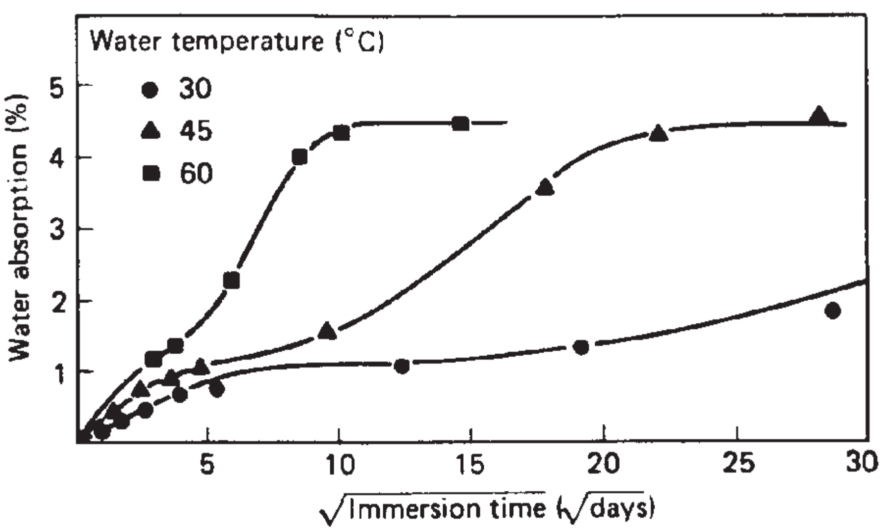


Figure 4-15 Time Varying Environmental Conditions in a Multi-layered Composite [Springer, *Environmental Effects on Composite Materials*]

Structural designers are primarily interested in the long term degradation of mechanical properties when composites are immersed in water. By applying curve-fitting programs to experimental data, extrapolations about long term behavior can be postulated. [4-28] Figure 4-16 depicts a 25 year prediction of shear strength for glass polyester specimens dried after immersion. Strength values eventually level off at about 60% of their original value, with the degradation process accelerated at higher temperatures. Figure 4-17 shows similar data for wet tensile strength. Experimental data at the higher temperatures is in relative agreement for the first three years.

Table 4-1 shows the apparent maximum moisture content and the transverse diffusivities for two polyester and one vinyl ester E-glass laminate. The numerical designation refers to fiber content by weight.

The water content of laminates cannot be compared directly with cast resin water contents, since the fibers generally do not absorb water. Water is concentrated in the resin (approximately 75% by volume for bidirectional laminates and 67% by volume for unidirectionals). [4-28]

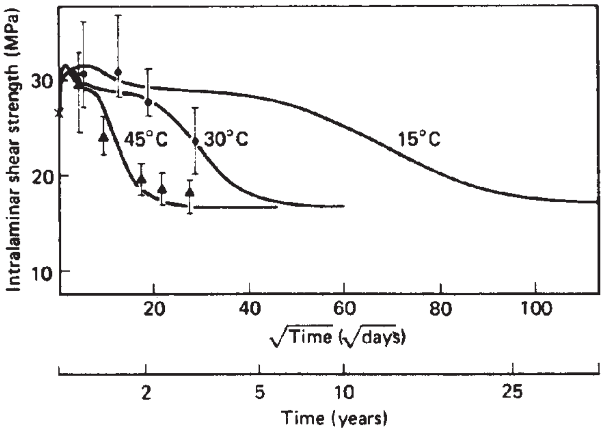


Figure 4-16 Change of Moisture Content with the Square Root of Time for "Fickian" Diffusion [Springer, *Environmental Effects on Composite Materials*]

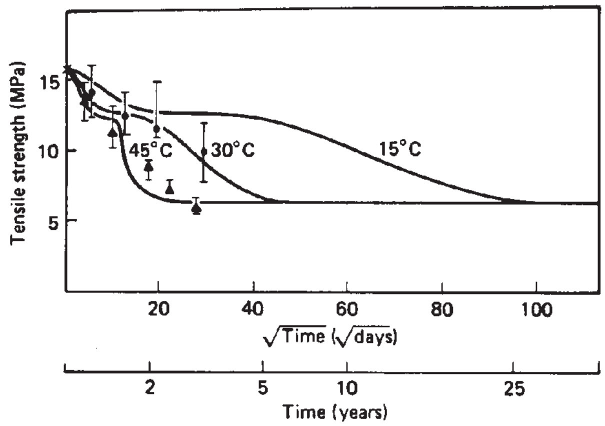


Figure 4-17 Predicted Dry Shear Strength versus Square Root of Immersion Time [Pritchard, *The Use of Water Absorbtion Kinetic Data to Predict Laminate Property Changes*]

Table 4-1 Apparent Maximum Moisture Content and Transverse Diffusivities of Some Polyester E-Glass and Vinyl Ester Laminates [Springer, *Environmental Effects on Composite Materials*]

Substance	Temp (°C)	Maximum Moisture Content*			Transverse Diffusivity†		
		SMC-R25	VE SMC-R50	SMC-R50	SMC-R25	VE SMC-R50	SMC-R50
50% Humidity	23	0.17	0.13	0.10	10.0	10.0	30.0
	93	0.10	0.10	0.22	50.0	50.0	30.0
100% Humidity	23	1.00	0.63	1.35	10.0	5.0	9.0
	93	0.30	0.40	0.56	50.0	50.0	50.0
Salt Water	23	0.85	0.50	1.25	10.0	5.0	15.0
	93	2.90	0.75	1.20	5.0	30.0	80.0
Diesel Fuel	23	0.29	0.19	0.45	6.0	5.0	5.0
	93	2.80	0.45	1.00	6.0	10.0	5.0
Lubricating Oil	23	0.25	0.20	0.30	10.0	10.0	10.0
	93	0.60	0.10	0.25	10.0	10.0	10.0
Antifreeze	23	0.45	0.30	0.65	50.0	30.0	20.0
	93	4.25	3.50	2.25	5.0	0.8	10.0

*Values given in percent

†Values given are $D_{22} \times 10^7$ mm^2/sec

Blisters

The blistering of gel coated, FRP structures has received much attention in recent years. The defect manifests itself as a localized raised swelling of the laminate in an apparently random fashion after a hull has been immersed in water for some period of time. When blisters are ruptured, a viscous acidic liquid is expelled. Studies have indicated that one to three percent of boats surveyed in the Great Lakes and England, respectively, have appreciable blisters. [4-29]

There are two primary causes of blister development. The first involves various defects introduced during fabrication. Air pockets can cause blisters when a part is heated under environmental conditions. Entrapped liquids are also a source of blister formation. Table 4-2 lists some liquid contaminate sources and associated blister discriminating features.

Table 4-2 Liquid Contaminate Sources During Spray-Up That Can Cause Blistering [Cook, *Polycor Polyester Gel Coats and Resins*]

Liquid	Common Source	Distinguishing Characteristics
Catalyst	Overspray, drips due to leaks of malfunctioning valves.	Usually when punctured, the blister has a vinegar-like odor; the area around it, if in the laminate, is browner or burnt color. If the part is less than 24 hours old, wet starch iodine test paper will turn blue.
Water	Air lines, improperly stored material, perspiration.	No real odor when punctured; area around blister is whitish or milky.
Solvents	Leaky solvent flush system, overspray, carried by wet rollers.	Odor; area sometimes white in color.
Oil	Compressor seals leaking.	Very little odor; fluid feels slick and will not evaporate.
Uncatalyzed Resin	Malfunctioning gun or ran out of catalyst.	Styrene odor and sticky.

Even when the most careful fabrication procedures are followed, blisters can still develop over a period of time. These type of blisters are caused by osmotic water penetration, a subject that has recently been examined by investigators. The osmotic process allows smaller water molecules to penetrate through a particular laminate, which react with polymers to form larger molecules, thus trapping the larger reactants inside. A pressure or concentration gradient develops, which leads to hydrolysis within the laminate. Hydrolysis is defined as decomposition of a chemical compound through the reaction with water. Epoxide and polyurethane resins exhibit better hydrolytic stability than polyester resins. In addition to the contaminants listed in Table 4-2, the following substances act as easily hydrolyzable constituents: [4-30]

- Glass mat binder;
- Pigment carriers;
- Mold release agents;

- Stabilizers;
- Promoters;
- Catalysts; and
- Uncross-linked resin components.

Blisters can be classified as either coating blisters or those located under the surface at substrate interfaces (see Figure 4-18). The blisters under the surface are more serious and will be of primary concern. Some features that distinguish the two types include:

- Diameter to height ratio of sub-gel blister is usually greater than 10:1 and approaches 40:1 whereas coating blisters have ratios near 2:1;
- Sub-gel blisters are much larger than coating blisters;
- The coating blister is more easily punctured than the sub-gel blister; and
- Fluid in sub-gel blisters is acidic (pH 3.0 to 4.0), while fluid in coating blisters has a pH of 6.5 to 8.0.

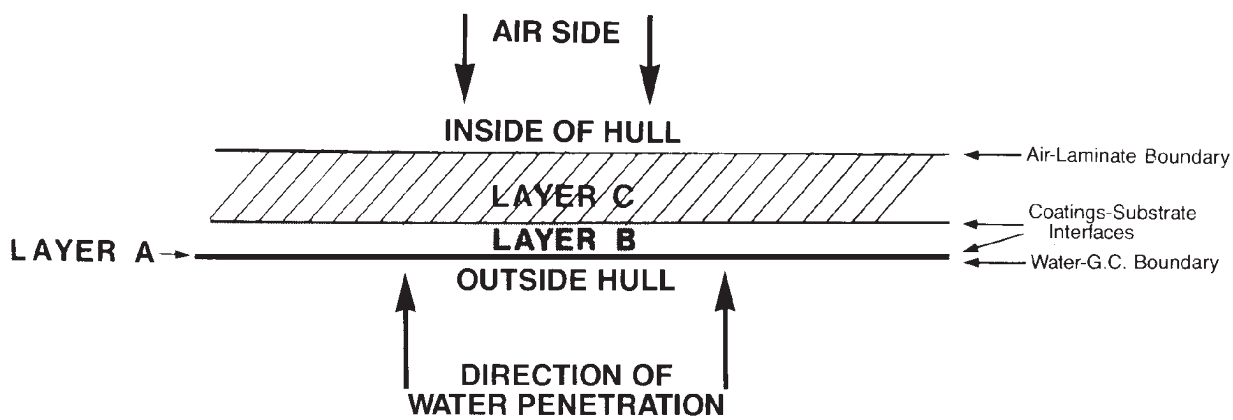


Figure 4-18 Structure Description for a Skin Coated Composite with: **Layer A** = Gel Coat, **Layer B** = Interlayer and **Layer C** = Laminate Substrate [Interplastic, *A Study of Permeation Barriers to Prevent Blisters in Marine Composites and a Novel Technique for Evaluating Blister Formation*]

Both types of blisters are essentially cosmetic problems, although sub-gel blisters do have the ability to compromise the laminate's integrity through hydrolytic action. A recent theoretical and experimental investigation [4-31] examined the structural degradation effects of blisters within hull laminates. A finite element model of the blister phenomena was created by progressively removing material from the surface down to the sixth layer, as shown in Figure 4-19. Strain gage measurements were made on sail and power boat hulls that exhibited severe blisters. The field measurements were in good agreement with the theoretically determined values for strength and stiffness. Stiffness was relatively unchanged, while strength values degraded 15% to 30%, usually within the margin of safety used for the laminates.

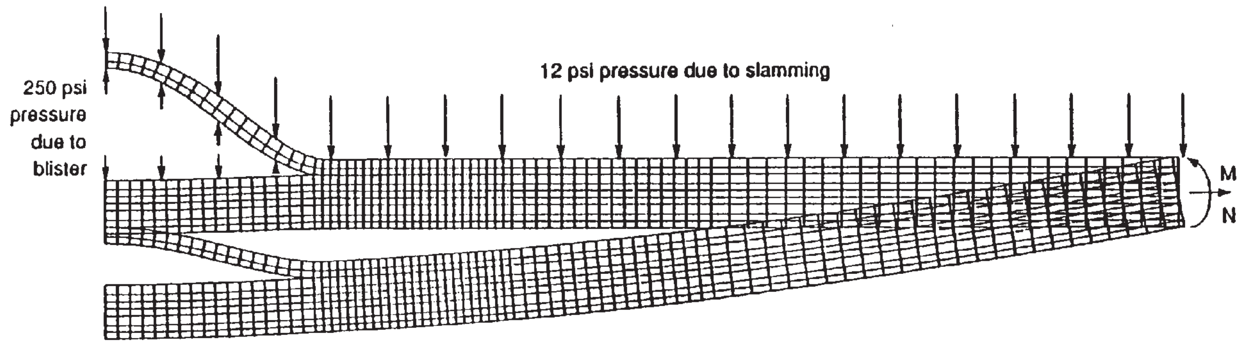


Figure 4-19 Internal Blister Axisymetric Finite Element Model [Kokarakis and Taylor, *Theoretical and Experimental Investigation of Blistered Fiberglass Boats*]

The fact that the distribution of blisters is apparently random has precluded any documented cases of catastrophic failures attributed to blistering. The Repair Section (page 285) of this document will deal with corrective measures to remove blisters.

As was previously mentioned, recent investigations have focused on what materials perform best to prevent osmotic blistering. Referring to Figure 4-18, Layer A is considered to be the gel coat surface of the laminate. Table 4-3 lists some permeation rates for three types of polyester resins that are commonly used as gel coats.

Table 4-3 Composition and Permeation Rates for Some Polyester Resins used in Gel Coats [Crump, *A Study of Blister Formation in Gel Coated Laminates*]

Resin	Glycol	Saturated Acid	Unsaturated Acid	Permeation Rate*	
				H_2O @ 77°F	H_2O @ 150°F
NPG Iso	Neopentyl glycol	Isophthalic acid	Maleic anhydride	0.25	4.1
NPG Ortho	Neopentyl glycol	Phthalic anhydride	Maleic anhydride	0.24	3.7
General Purpose	Propylene glycol	Phthalic anhydride	Maleic anhydride	0.22	3.6
*grams/cubic centimeter per day x 10^{-4}					

Investigators at the Interplastic Corporation concentrated their efforts on determining an optimum barrier ply, depicted as Layer B in Figure 4-18. Their tests involved the complete submersion of edge-sealed specimens that were required to have two gel coated surfaces. The conclusion of this study was that a vinyl ester cladding applied on an orthophthalic laminating resin reinforced composite substantially reduced blistering.

Investigators at the University of Rhode Island, under the sponsorship of the U.S. Coast Guard, conducted a series of experiments to test various coating materials and methods of application. Table 4-4 summarizes the results of tests performed at 65°C. Blister severity was subjectively evaluated on a scale of 0 to 3. The polyester top coat appeared to be the best performing scheme.

Table 4-4 Results from URI Coating Investigation
[Marino, *The Effects of Coating on Blister Formation*]

Coating Scheme	Surface Treatment	Blister Initiation Time (days)	Blister Severity	Blisters Present?
Epoxy top coat	none	5	3	Yes
	sanding	5	1	Yes
	acetone wipe	5	1	Yes
	both	5	1	Yes
Polyurethane top coat	none	5	2	Yes
	sanding	14	1	Yes
	acetone wipe	?	1	Yes
	both	?	1	Yes
Polyester top coat	none	-	0	No
	sanding	-	0	No
	acetone wipe	-	0	No
	both	-	0	No
Epoxy top coat over epoxy	none	8	3	Yes
	sanding	8	1	Yes
	acetone wipe	8	2-3	Yes
	both	8	2	Yes
Polyurethane top coat over polyurethane	none	7	1	Yes
	sanding	7	1	Yes
	acetone wipe	7	1	Yes
	both	7	1	Yes
Polyester top coat over polyester	none	8	3	No
	sanding	-	0	No
	acetone wipe	8	2	No
	both	8	1	No
Epoxy top coat over polyurethane	none	8	3	Yes
	sanding	8	2	Yes
	acetone wipe	17	1-2	?
	both	19	2	Yes
Polyurethane top coat over epoxy	none	11	3	Yes
	sanding	-	0	Yes
	acetone wipe	11	1-3	Yes
	both	-	1	Yes

Coating Scheme	Surface Treatment	Blister Initiation Time (days)	Blister Severity	Blisters Present?
Polyurethane top coat over polyester	none	6	3	Yes
	sanding	6	3	Yes
	acetone wipe	6	3	Yes
	both	6	1	Yes
Epoxy top coat over polyester	none	9	3	Yes
	sanding	9	3	Yes
	acetone wipe	9	3	Yes
	both	9	3	Yes

Blister Severity Scale

0 no change in the coated laminate
1 questionable presence of coating blisters; surface may appear rough, with rare, small pin size blisters
2 numerous blisters are present
3 severe blistering over the entire laminate surface

Case Histories

Advocates of fiberglass construction have often pointed to the long term maintenance advantages of FRP materials. Wastage allowances and shell plating replacement associated with corrosion and galvanic action in metal hulls is not a consideration when designing fiberglass hulls. However, concern over long term degradation of strength properties due to in-service conditions prompted several studies in the 60s and 70s. The results of those investigations along with some case histories that illustrate common FRP structural failures, are presented in this section. It should be noted that documented failures are usually the result of one of the following:

- Inadequate design;
- Improper selection of materials; or
- Poor workmanship.

US Coast Guard 40 foot Patrol Boats

These multipurpose craft were developed in the early 1950s for law enforcement and search and rescue missions. The boats are 40 feet overall with an 11 foot beam and displaced 21,000 pounds. Twin 250 horsepower diesel engines produced a top speed of 22 knots. Single skin FRP construction was reinforced by transverse aluminum frames, a decidedly conservative approach at the time of construction. Laminate schedules consisted of alternating plies of 10 ounce boat cloth and 1½ ounce mat at ¾ inch for the bottom and ⅜ inch for the sides.

In 1962, Owens-Corning Fiberglass and the U.S. Coast Guard tested panels cut from three boats that had been in service 10 years. In 1972, more extensive tests were performed on a larger population of samples taken from CG Hull 40503, which was being retired after 20 years in service. It should be noted that service included duty in an extremely polluted ship channel where contact with sulfuric acid was constant and exposure to extreme temperatures during one fire fighting episode. Total operating hours for the vessel was 11,654. Visual examination of sliced specimens indicated that water or other chemical reactants had not entered the laminate. The comparative physical test data is presented in Table 4-5.

Table 4-5 Physical Property Data for 10 Year and 20 Year Tests of USCG Patrol Boat [Owens-Corning Fiberglas, *Fiber Glass Marine Laminates, 20 Years of Proven Durability*]

Hull CG 40503		10 Year Tests	20 Year Tests
Tensile Strength	Average psi	5990	6140
	Number of samples	1	10
Compressive Strength	Average psi	12200	12210
	Number of samples	2	10
Flexural Strength	Average psi	9410	10850
	Number of samples	1	10
Shear Strength	Average psi	6560	6146
	Number of samples	3	10

Submarine Fairwater

In the early 1950s, the U.S. Navy developed a fiberglass replacement for the aluminum fairwaters that were fitted on submarines. The fairwater is the hydrodynamic cowling that surrounds the submarine's sail, as shown in Figure 4-20. The motivation behind this program was electrolytic corrosion and maintenance problems. The laminate used consisted of style 181 Volan glass cloth in a general purpose polyester resin that was mixed with a flexible resin for added toughness. Vacuum bag molding was used and curing took place at room temperature.

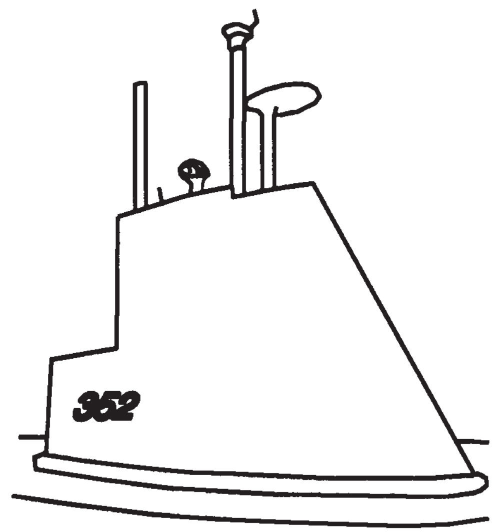


Figure 4-20 Submarine Fairwater for the *U.S.S. Halfbeak* [Lieblein, *Survey of Long-Term Durability of Fiberglass-Reinforced Plastic Structures*]

The fairwater installed on the ***U.S.S. Halfbeak*** was examined in 1965 after 11 years in service. The physical properties of the tested laminates are shown in Table 4-6. After performing the tests, the conclusion that the materials were not adversely affected by long term exposure to weather was reached. It should be noted that a detailed analysis of the component indicated that a safety factor of four was maintained throughout the service life of the part. Thus, the mean stress was kept below the long term static fatigue strength limit, which at the time was taken to be 20 to 25 percent of the ultimate strength of the laminate.

Table 4-6 Property Tests of Samples from Fairwater of U.S.S. Halfbeak [Fried & Graner, *Durability of Reinforced Plastic Structural Materials in Marine Service*]

Property	Condition	Original Data (1954)*	1965 Data 1st Panel	1965 Data 2nd Panel	1965 Data Average
Flexural Strength, psi	Dry	52400	51900	51900	51900
	Wet†	54300	46400	47300	46900
Flexural Modulus, psi x 10^{-6}	Dry	2.54	2.62	2.41	2.52
	Wet	2.49	2.45	2.28	2.37
Compressive Strength, psi	Dry	—	40200	38000	39100
	Wet	—	35900	35200	35600
Barcol Hardness	Dry	55	53	50	52
Specific Gravity	Dry	1.68	1.69	1.66	1.68
Resin Content	Dry	47.6%	47.4%	48.2%	47.8%

* Average of three panels
† Specimen boiled for two hours, then cooled at room temperature for one hour prior to testing

Gel Coat Cracking

Hairline cracks in exterior gel coat surfaces are traditionally treated as a cosmetic problem. However, barring some deficiency in manufacturing, such as thickness gauging, catalyzation or mold release technique, gel coat cracks often are the result of design inadequacies and can lead to further deterioration of the laminate. Gel coat formulations represent a fine balance between high gloss properties and material toughness. Designers must be constantly aware that the gel coat layer is not reinforced, yet it can experience the highest strain of the entire laminate because it is the farthest away from the neutral axis.

This section will attempt to classify types of get coat cracks and describe the stress field associated with them. [4-32] Figure 4-21 shows a schematic representation of three types of gel coat cracks that were analyzed by Smith using microscopic and fractographic techniques. That investigation lead to the following conclusions:

Type I

These are the most prevalent type of cracks observed by marine surveyors and have traditionally been attributed to overly thick gel coat surface or impact from the opposite side of the laminate. Although crack patterns can become rather complex, the source can usually be traced radially to the area of highest crack density. The dominant stress field is one of highly localized tensile stresses, which can be the result of internal braces (stiffener hard spots) or overload in bending and flexing (too large a panel span for laminate). Thermal stresses created by different thermal expansion coefficients of materials within a laminate can create cracks. This problem is especially apparent when plywood is used as a core. Residual stress can also influence the growth of Type I cracks.

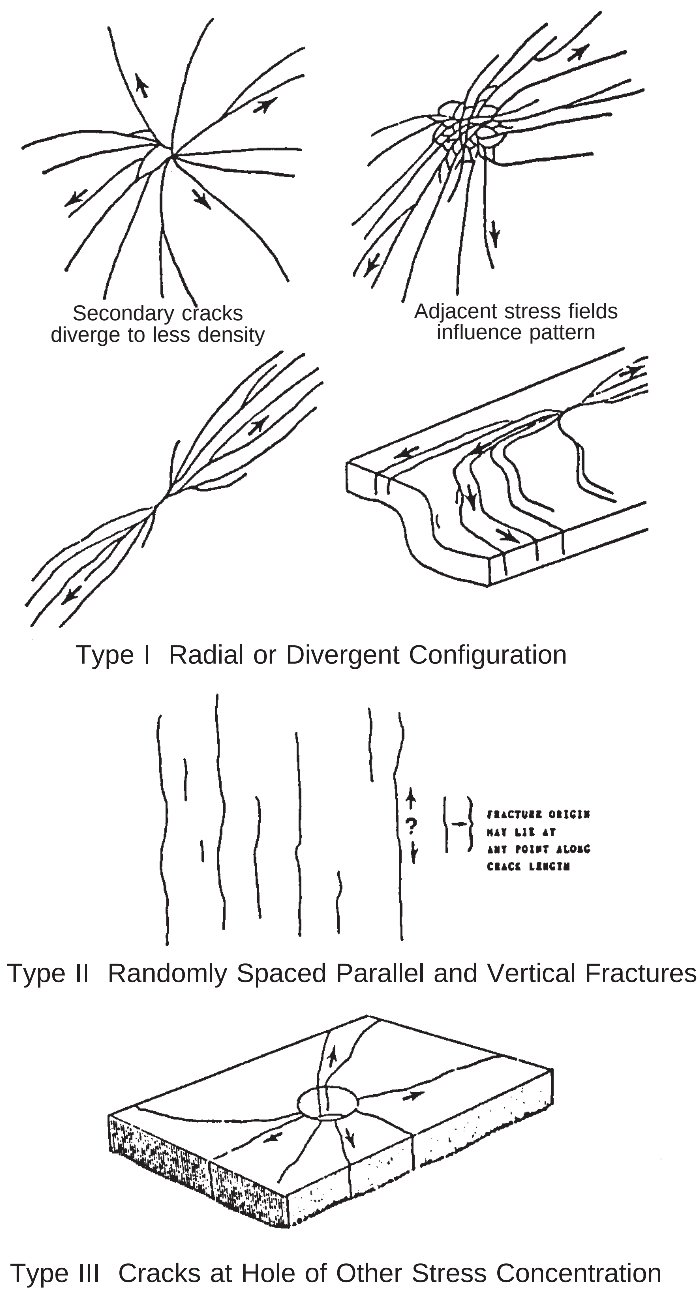


Figure 4-21 Schematic Representations of Gel Coat Crack Patterns [Smith, *Cracking of Gel Coated Composites*]

Cracks tend to initiate at points of non-uniformity in the laminate, such as voids or areas that are resin rich or starved. The propagation then proceeds in a bilateral fashion, finally into the laminate itself.

Type II

Type II cracks are primarily found in hull structures and transoms, although similar fractures have been noted along soles and combings [4-33]. In the latter instance, insufficient support has been cited as the contributing cause, with the pattern of cracking primarily attributable to the geometry of the part. The more classical Type II cracks are the result of thermal fatigue, which is the dominant contributing factor for crack nucleation. The parallel nature of the cracks makes it difficult to pinpoint the exact origin of the failure, although it is believed that cracks nucleate at fiber bundles perpendicular to the apparent stress fields. Other factors contributing to this type of crack growth are global stress fields and high thermal gradients.

Type III

Cracking associated with holes drilled in the laminate are quite obvious. The hole acts as a notch or stress concentrator, allowing cracks to develop with little externally applied stress. Factors contributing to the degree of crack propagation include:

- Global stress field;
- Method of machining the hole; and
- Degree of post cure.

Core Separation in Sandwich Construction

It has been shown that sandwich construction can have tremendous strength and stiffness advantages for hull panels, especially when primary loads are out of plane. As a rule, material costs will also be competitive with single-skin construction because of the reduced number of plies in a laminate. However, construction with a core material requires additional labor skill to ensure proper bonding to the skins. Debonding of skins from structural cores is probably the single most common mode of laminate failure seen in sandwich construction. The problem may either be present when the hull is new or manifest itself over a period of time under in-service load conditions.

Although most reasons for debonding relate to fabrication techniques, the designer may also be at fault for specifying too thin a core, which intensifies the interlaminar shear stress field when a panel is subject to normal loads. Problems that can be traced to the fabrication shop include:

- Insufficient preparation of core surface to resist excessive resin absorption;
- Improper contact with first skin, especially in female molds;
- Application of second skin before core bedding compound has cured;
- Insufficient bedding of core joints; and
- Contamination of core material (dirt or moisture).

Selection of bonding resin is also critical to the performance of this interface. Some transition between the "soft" core and relatively stiff skins is required. This can be achieved if a resin with a reduced modulus of elasticity is selected.

Load sources that can exacerbate a poorly bonded sandwich panel include wave slamming, dynamic deck loading from gear or personnel, and global compressive loads that tend to seek out instable panels. Areas that have been shown to be susceptible to core debonding include:

- Stress concentrations will occur at the face to core joint of scrim-cloth or contoured core material if the voids are not filled with a bonding agent, as shown in Figure 4-22;
- Areas with extreme curvature that can cause difficulties when laying the core in place;
- Panel locations over stiffeners;
- Centers of excessively large panels;
- Cockpit floors; and
- Transoms.

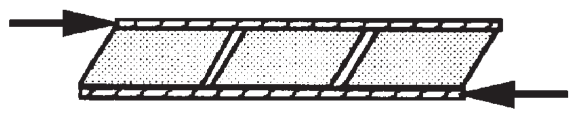


Figure 4-22 Illustration of Stress Concentration Areas in Unfilled Contoured Core Material [Morgan, *Design to the Limit: Optimizing Core and Skin Properties*]

Failures in Secondary Bonds

Secondary bond failures are probably the most common structural failure on FRP boats. Due to manufacturing and processing limitations, complete chemical bonding strength is not always obtained. Additionally, geometries of secondarily bonded components usually tend to create stress concentrations at the bond line. Some specific areas where secondary bond failures have been noted include:

- Stiffeners and bulkhead attachments;
- Furniture and floor attachment; and
- Rudder bearing and steering gear support.

Ultraviolet Exposure

The three major categories of resins that are used in boat building, polyester, vinyl ester and epoxy, have different reactions to exposure to sunlight. Sunlight consists of ultraviolet rays and heat.

Epoxies are generally very sensitive to ultraviolet (UV) light and if exposed to UV rays for any significant period of time, the resins will degrade to the point where they have little, if any, strength left to them. The vinyl esters, because there are epoxy linkages in them, are also sensitive to UV and will degrade with time, although in general not as rapidly as an epoxy. Polyester, although it is somewhat sensitive to UV degradation, is the least sensitive of the three to UV light.

The outer surface of most boats is covered with a gel coat. Gel coats are based on ortho or isopolyester resin systems that are heavily filled and contain pigments. In addition, often there is a UV screen added to help protect the resin, although for most gel coats the pigment itself serves as the UV protector.

In general, the exposure of the gel coats to UV radiation will cause fading of the color which is associated with the pigments themselves and their reaction to sunlight, but also on white or off-white gel coats UV exposure can cause yellowing. The yellowing is a degradation of the resin rather than the pigments and will finally lead to the phenomenon known as “chalking.” Chalking occurs when the very thin outer coating of resin degrades under the UV light to the point where it exposes the filler and some of the pigment in the gel coat. The high gloss finish that is typical of gel coats is due to that thin layer. Once it degrades and disappears, the gloss is gone and what's left is still a colored surface that it is no longer shiny. Because the pigments are no longer sealed by the thin outer coating of resin, they actually can degrade and lose some of their color and they eventually loosen up from the finish to give a kind of a chalky surface effect.

There are some gel coats that are based on vinyl ester resin. These are not generally used in the marine industry, but some boat manufacturers are starting to use them below the waterline to prevent blistering, since vinyl ester resins are not typically susceptible to blistering. However, if these resins are used on the top side or the decks of a boat, they will suffer yellowing and chalking very quickly as compared to a good ortho or isopolyester gel coat.

Temperature Effects

In addition to UV degradation caused by sunlight, the effects of heat must also be considered. The sun can significantly heat up the gel coat and the laminate beneath it. The amount of damage that can be done depends on a number of factors. First, the thermal expansion coefficient of fiberglass is very different from that of resin. Thus, when a laminate with a high glass content is heated significantly, the fiberglass tends to be relatively stable, whereas the resin tries to expand but can't because it's held in place by the glass. The result of this is that the pattern of the fiberglass will show through the gel coat in many cases, a phenomenon known as “print through.” Of course, if reinforcing fibers are used which have thermal expansion coefficients similar to the resins, it is less likely that print through will occur.

Another consideration in addition to the thermal coefficient of expansion is the temperature at which the resin was cured. Most polyester resins have a heat distortion temperature of around 150-200°F. This means that when the resin becomes heated to that temperature it has gone above the cure temperature and the resin will become very soft. When resin becomes soft, the laminate becomes unstable. The resin can actually cure further when it's heated to these temperatures. When it cools down the resin will try to shrink, but since it's been set at the higher temperature and the glass doesn't change dimensions very much, the resin is held in place by the glass, thereby creating very large internal stresses solely due to these thermal effects. Although this can happen also in a new laminate when it's cured, it is most often found in a laminate that's exposed to the sun and is heated higher than its heat distortion temperature. This can be a problem with all room temperature thermosetting resins, polyester vinyl ester and epoxies, although it is less likely to be a problem with vinyl ester and epoxy than with polyester, because the vinyl esters and epoxies usually cure at a higher exotherm temperature.

As mentioned above, the heat distortion temperature of polyester resins can range from about 150°-200°. In Florida or the tropics, it's not uncommon to get temperatures in excess of 150° on boats with white gel coats. Temperatures have been measured as high as 180° on the decks of boats with red gel coat, close to 200° on the decks of boats with dark blue gel coat and well over 200° on the decks of boats with black gel coat. That's one of the reasons why there are very few boats with black gel coat. Some sport fishing boats or other boats are equipped with a wind screen which, rather than being clear, is actually fiberglass coated with black gel coat for a stylish appearance. This particular part of these boats suffers very badly from print through problems because the heat distortion temperature or the resin in the gel coat is exceeded. Obviously, during each day and night much temperature cycling occurs; the laminate will get hot in the day, cool off at night, get hot again the next day, etc. Even if the resin is postcured to some extent, it will still suffer from this cyclic heating and cooling. These temperature cycles tend to produce internal stresses which then cause the laminate to fatigue more rapidly than it normally would.

Another thermal phenomena is fatigue caused by shadows moving over the deck of a boat that's sitting in the sun. As the sun travels overhead, the shadow will progress across the deck. At the edge of the shadow there can be a very large temperature differential, on the order of 20°-30°F. As a result, as that shadow line travels there is a very sharp heating or cooling at the edge, and the differential causes significant stress right at that point. That stress will result in fatigue of the material. Boats that are always tied up in the same position at the dock where the same areas of the boat get these shadows traveling across them, can actually suffer fatigue damage with the boat not even being used.

Another environmental effect not often considered by composite boat designers is extreme cold. Most resins will absorb some amount of moisture, some more than others. A laminate which has absorbed a significant amount of moisture will experience severe stresses if the laminate becomes frozen, since water expands when it freezes. This expansion can generate significant pressures in a laminate and can actually cause delamination or stress cracking.

Another problem with cold temperatures concerns the case of a laminate over plywood. Plywood is relatively stable thermally and has a low coefficient of thermal expansion as compared to the resins in the fiberglass laminated over it. If the fiberglass laminate is relatively thin and the plywood fairly thick, the plywood will dominate. When the resin tries to contract in cold temperatures, the plywood will try to prevent it from contracting and local cracking will occur in the resin because the plywood is not homogeneous. There is a grain to the wood, so some areas won't restrain the contracting resin and other areas will. As a result, spiderweb cracking can occur. This effect has been noted on new boats that have been built in warmer climates and sent to northern regions.

Failure Modes

The use of engineered composite structures requires an insight into the failure modes that are unique to these types of materials. Some people say that composites are "forgiving," while others note that catastrophic failures can be quite sudden. Because laminates are built from distinct plies, it is essential to understand how loads are "shared" among the plies. It is also critical to distinguish between resin dominated failures or fiber dominated failures. Armed with a thorough understanding of the different ways that a structure can fail makes it possible to design a laminate that will "soften" at the point of potential failure and redistribute stress.

Failures in composite structures can be classified as by either "strength" or "stiffness" dominated. Strength limited failures occur when unit stress exceeds the load carrying capability of the laminate. Stiffness failures result when displacements exceed the strain limits (elongation to failure) of the laminate.

Tensile failures of composite materials is fairly rare, as filament reinforcements are strongest in tension along their primary axis. Tensile loading in an off-axis direction is a different story. Resin and fiber mechanical properties vary widely in tension, so each must be studied for stress or strain limited failure with off-axis loading scenarios.

Compressive failures in composites are probably the hardest to understand or predict. Failures can occur at a very small-scale, such as the compression or buckling of individual fibers. With sandwich panels, skin faces can wrinkle or the panel itself may become unstable. Indeed, incipient failure may occur at some load well below an ultimate failure.

Out-of-plane loading, such as hydrostatic force, creates flexural forces for panels. Classic beam theory would tell us that the loaded face is in compression, the other face is in tension, and the core will experience some shear stress distribution profile. For three-dimensional panels, predicting through-thickness stresses is somewhat more problematic. Bending failure modes to consider include core shear failure, core-to-skin debonds, and skin failures (tension, compression, and local).

Although composite structures are not subject to corrosion, laminates can sustain long-term damage from ultraviolet (UV) and elevated temperature exposure. Based on the number of pioneering FRP recreational craft that are still in service, properly engineered laminates should survive forty-plus years in service.

Lastly, the performance of composite structures in fires is often a factor that limits the use of these materials. Composites are excellent insulators, which tends to confine fires to the space of origin. However, as an organic material the polymeric resin systems will burn when exposed to a large enough fire. Tests of various sizes exist to understand the performance marine composite materials system during shipboard fires.

Tensile Failures

The tensile behavior of engineered composite materials is generally characterized by stress-strain curves, such as those shown in Figure 4-23. The ASTM *Standard Test Method for Tensile Properties of Plastics*, D 638-84, defines several key tensile failure terms as follows:

Tensile Strength	=	Maximum tensile strength during test
Strain	=	The change in length per unit
Yield Point	=	First point on the stress-strain curve where increased strain occurs without increased stress
Elastic limit	=	The greatest stress that a material can withstand without permanent deformation
Modulus of elasticity	=	The ratio of stress to strain below the proportional limit
Proportional limit	=	Greatest stress that a material can withstand with linear behavior

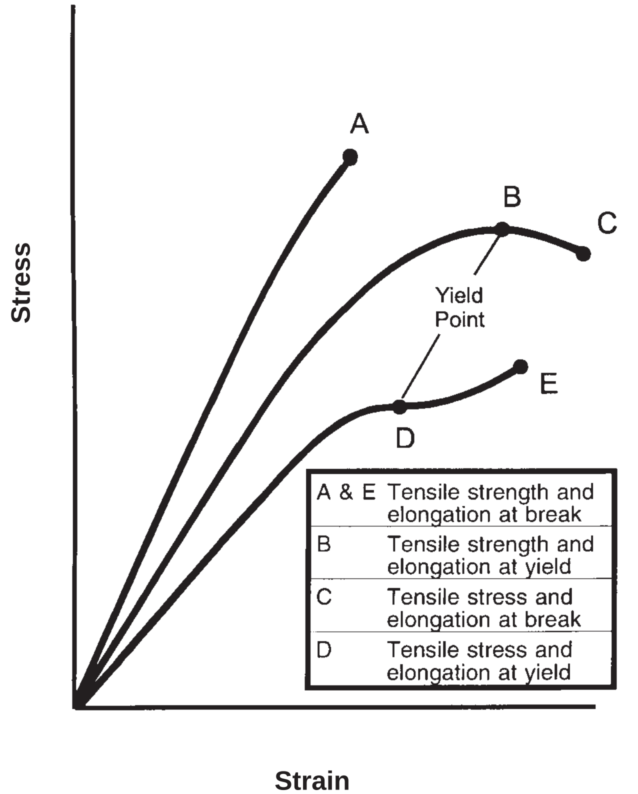


Figure 4-23 Tensile Failure Modes of Engineered Plastics Defined by ASTM [ASTM D 638-84, ASTM, West Conshohocken, PA]

Tensile tests are usually performed under standard temperature and humidity conditions and at relatively fast speeds (30 seconds to 5 minutes). Test conditions can vary greatly from in-service conditions and the designer is cautioned when using single-point engineering data generated under laboratory test conditions. Some visible signs of tensile failures in plastics are:

Crazing: Crazes are the first sign of surface tensile failures in thermoplastic materials and gel coat finishes. Crazes appear as clean hairline fractures extending from the surface into the composite. Crazes are not true fractures, but instead are combinations of highly oriented "fibrils" surrounded by voids. Unlike fractures, highly crazed surfaces can transmit stress. Water, oils, solvents and the environment can accelerate crazing.

Cracks: Cracking is the result of stress state and environment. Cracks have no fibrills, and thus cannot transmit stress. Cracks are a result of embrittlement, which is promoted by sustained elevated temperature, UV, thermal and chemical environments in the presence of stress or strain. This condition is also termed "stress-cracking."

Stress whitening: This condition is associated with plastic materials that are stretched near their yield point. The surface takes on a whitish appearance in regions of high stress. [4-34]

Membrane Tension

Large deflections of panels that are constrained laterally at their edges will produce tensile stresses on both faces due to a phenomena called “membrane” tension. Figure 4-24 illustrates this concept and the associated nomenclature. The ASCE ***Structural Plastics Design Manual*** [4-34] provides a methodology for approximating large deflections and stresses of isotropic plates when subjected to both bending and membrane stress. For long rectangular plates with fixed ends, the uniform pressure, q, is considered to be the sum of q_b, the pressure resisted by bending and q_m, the pressure resisted by membrane tension. Similarly, the maximum deflection, w_{max}, is defined as the sum of deflection due to plate bending and membrane action. ASCE defines the deflection due to bending as:

$$w_c = 0.156 \frac{(1-\nu^2)\, q_b\, b^4}{E\, t^3} \qquad (4\text{-}8)$$

solving (6-1) for “bending pressure”:

$$q_b = \frac{6.4\, w_c\, E\, t^3}{(1-\nu^2)\, b^4} \qquad (4\text{-}9)$$

where:

E = material stiffness (tensile)

ν = Poisson's ratio

t = plate thickness

b = span dimension

The deflection of the plate due only to membrane action is given as:

$$w_c = 0.41 \left[\frac{(1-\nu^2)\, q_m\, b^4}{E\, t}\right]^{1/3} \qquad (4\text{-}10)$$

solving (4-10) for “membrane pressure”:

$$q_m = \frac{14.5\, w_c^3\, E\, t}{(1-\nu^2)\, b^4} \qquad (4\text{-}11)$$

Combining (4-9) and (4-11) results in the following expression for total load:

$$q = \frac{w_c\, E\, t^3}{(1-\nu^2)\, b^4}\left(6.4 + 14.5\frac{w_c^2}{t^2}\right) \qquad (4\text{-}12)$$

The ***Manual*** [4-34] suggests that trail thicknesses, *t*, be tried until acceptable deflections or maximum stresses result. Bending stress for long plates is given as:

$$\sigma_{cby} = 0.75\, q_b\, b^2 \tag{4-13}$$

Membrane stress is given as:

$$\sigma_{cy} = 0.30 \sqrt[3]{\frac{q_m^2\, b^2\, E}{(1-\nu^2)\, t^2}} \tag{4-14}$$

The total stress is the sum of equations (4-13) and (4-14). With thick or sandwich laminates, the skin on the loaded side can be in compression, and thus the combined bending and membrane stress may actually be less than the bending stress alone.

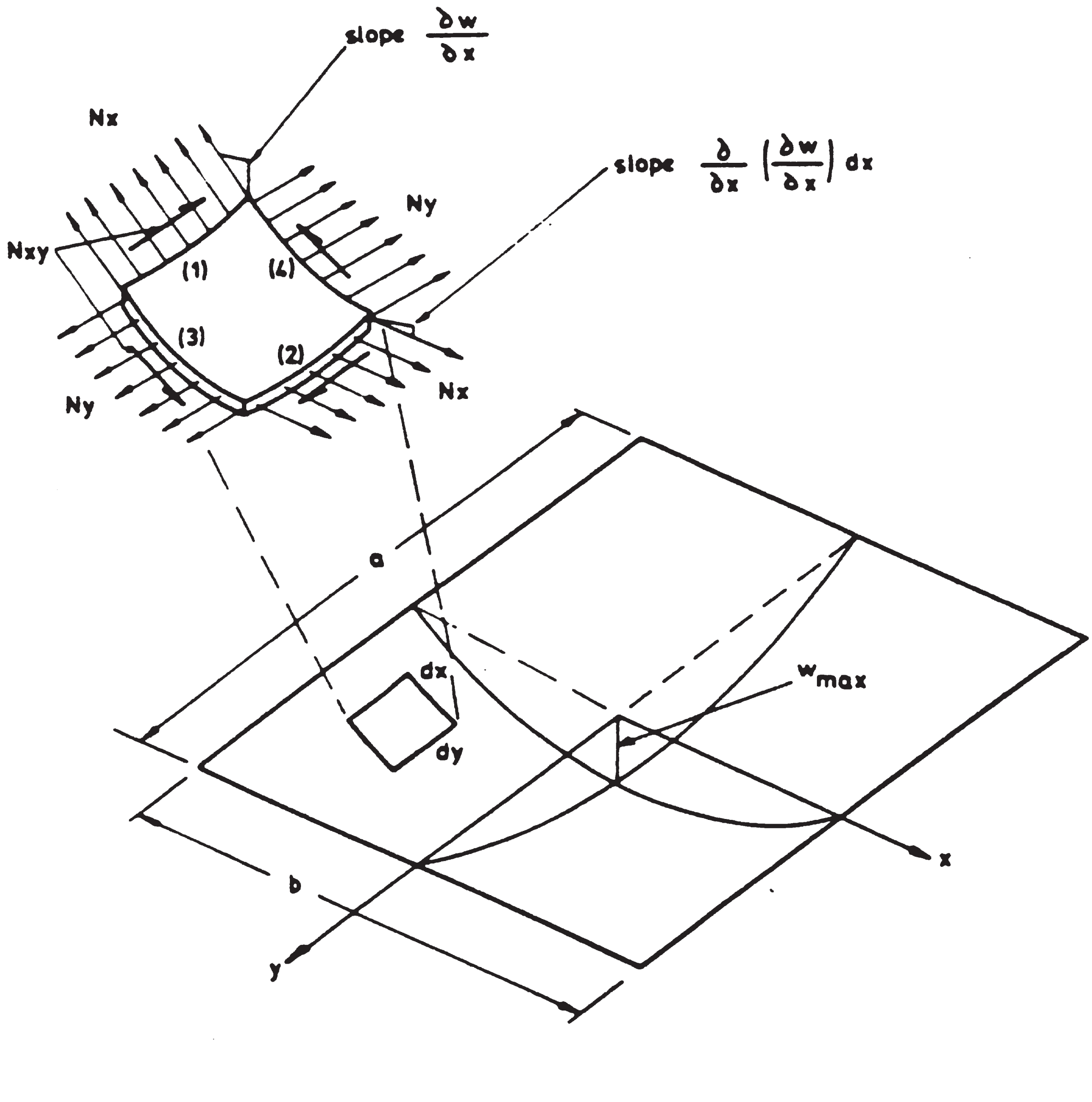


Figure 4-24 Illustration of Membrane Tension in a Deflected Panel

Compressive Failures

Analytical methods for predicting compressive failures in solid and sandwich laminates are presented in Chapter Three. The following discussion describes some of the specific failure modes found in sandwich laminates. Figure 4-25 illustrates the compressive failure modes considered. Note that both general and local failure modes are described.

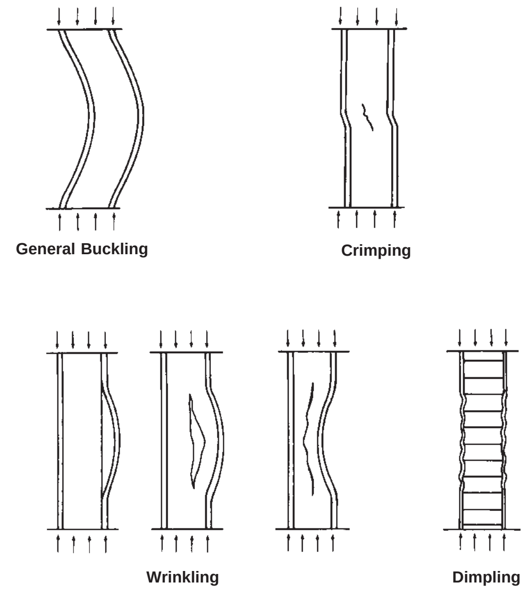


Figure 4-25 Compressive Failure Modes of Sandwich Laminates [*Sandwich Structures Handbook*, Il Prato]

The type of compressive failure mode that a sandwich laminate will first exhibit is a function of load span, skin to core thickness ratio, the relationship of core to skin stiffness and skin-to-core bond strength.

Large unsupported panel spans will tend to experience general buckling as the primary failure mode. If the core shear modulus is very low compared to the stiffness of the skins, then crimping may be the first failure mode observed. Very thin skins and poor skin-to-core bonds can result in some type of skin wrinkling. Honeycomb cores with large cell sizes and thin skins can exhibit dimpling.

General Buckling

Formulas for predicting general or panel buckling are presented in Chapter Three. As hull panels are generally sized to resist hydrodynamic loads, panel buckling usually occurs in decks or bulkheads. Transversely-framed decks may be more than adequate to resist normal loads, while still being susceptible to global, hull girder compressive loads resulting from longitudinal bending moments.

Bulkhead scantling development, especially with multi-deck ships, requires careful attention to anticipated in-plane loading. Superposition methods can be used when analyzing the case of combined in-plane and out-of-plane loads. This scenario would obviously produce buckling sooner than with in-plane loading alone. The general Euler buckling formula for collapse is:

$$\sigma_{critical} = \frac{\pi^2 EI}{l^2_{cr}} \qquad (4\text{-}15)$$

The influence of determining an end condition to use for bulkhead-to-hull or bulkhead-to-deck attachment is shown in Figure 4-26. Note that $\sigma_{critical}$ required for collapse is 16 times greater for a panel with both ends fixed, as compared to a panel with one fixed end and one free end.

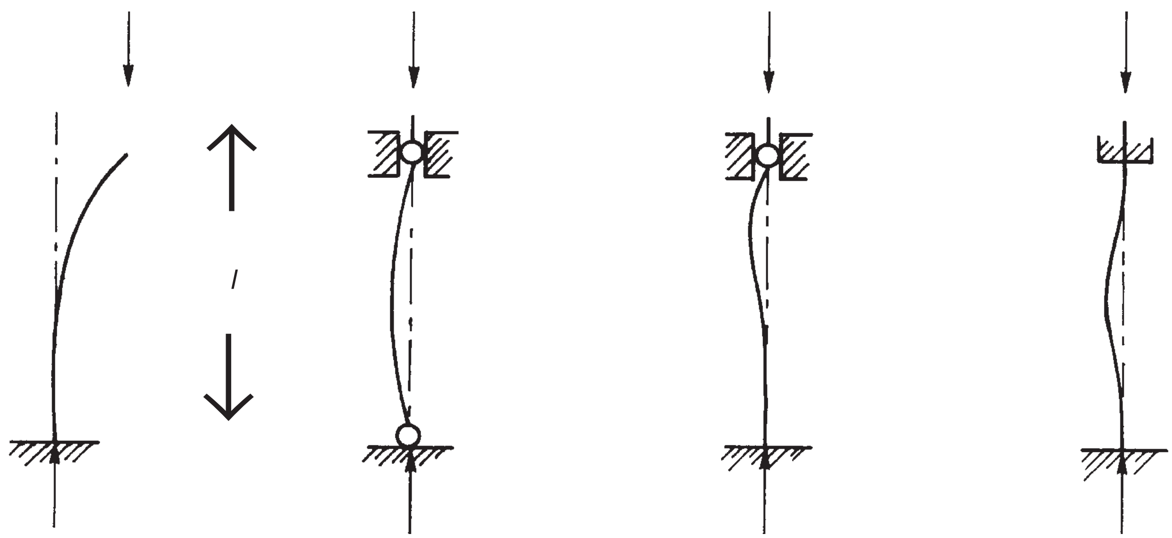


Figure 4-26 Critical Length for Euler Buckling Formula Based on End Condition [*Sandwich Structures Handbook*, Il Prato]

Crimping & Skin Wrinkling

Shear crimping of the core will occur when the core shear modulus is too low to transfer load between the skins. When the skins are required to resist the entire compressive load without help from the core, the panel does not have the required overall moment of inertia, and will fail along with the core.

Skin wrinkling is a form of local buckling whereupon the skins separate from the core and buckle on their own. Sandwich skins can wrinkle symmetrically; in a parallel fashion (anti-symmetric), or one side only. The primary structural function of the skin-to-core interface in sandwich laminates is to transfer shear stress between the skins and the core. This bond relies on chemical and mechanical phenomena. A breakdown of this bond and/or buckling instability of the skins themselves (too soft or too thin) can cause skin wrinkling.

Dimpling with Honeycomb Cores

Skin dimpling with honeycomb cores is a function the ratio of skin thickness to core cell size, given by the following relationship:

$$\sigma_{critical} = 2\frac{E_{skin}}{\left(1-\mu^2{}_{skin}\right)}\left(\frac{t_{skin}}{c}\right) \qquad (4\text{-}16)$$

where:

t_{skin} = skin thickness

c = core cell size given as an inscribed circle

Bending Failure Modes

The distribution of tensile, compressive and shear stresses in solid laminates subject to bending moments follows elementary theory outlined by Timoshenko [4-35]. Figure 4-27 shows the nomenclature used to describe bending stress. The general relationship between tensile and compressive stress and applied moment, as a function of location in the beam is:

$$\sigma_x = \frac{M\ y}{I_z} \qquad (4\text{-}17)$$

where:

σ_x = skin tensile or compressive stress

M = applied bending moment

y = distance from the neutral axis

I_z = moment of inertia about the "z" axis

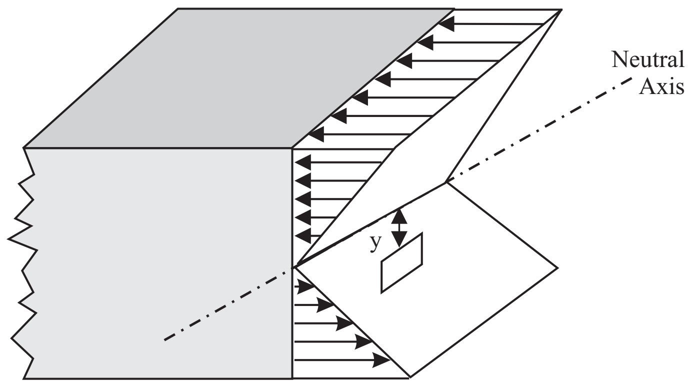


Figure 4-27 Nomenclature for Describing Bending Stress in Solid Beam

As is illustrated in Figure 4-27, the in-plane tensile and compressive stresses are maximum at the extreme fibers of the beam (top and bottom).

Shear stresses resulting from applied bending moments, on the other hand, are zero at the extreme fibers and maximum at the neutral axis. Figure 4-28 shows conceptually the shearing forces that a beam experiences. The beam represented is composed of two equal rectangular bars used to illustrate the shear stress field at the neutral axis.

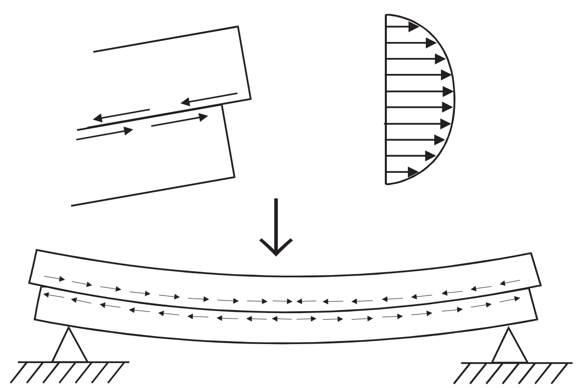


Figure 4-28 Nomenclature for Describing Shear Stress in Solid Beam

Formulas for general and maximum shear stress as a function of shear load, V, are:

$$\tau_{xy} = \frac{V}{2I_z}\left(\frac{h^2}{4} - y^2\right) \qquad (4\text{-}18)$$

$$\tau_{max} = \frac{Vh^2}{8I_z} \qquad (4\text{-}19)$$

Sandwich Failures with Stiff Cores

Sandwich structures with stiff cores efficiently transfer moments and shear forces between the skins, as illustrated in Figure 4-29. Elementary theory for shear-rigid cores assumes that the total deflection of a beam is the sum of shear and moment induced displacement:

$$\delta = \delta_m + \delta_v \qquad (4\text{-}20)$$

where:

δ_v = shear deflection

δ_m = moment deflection

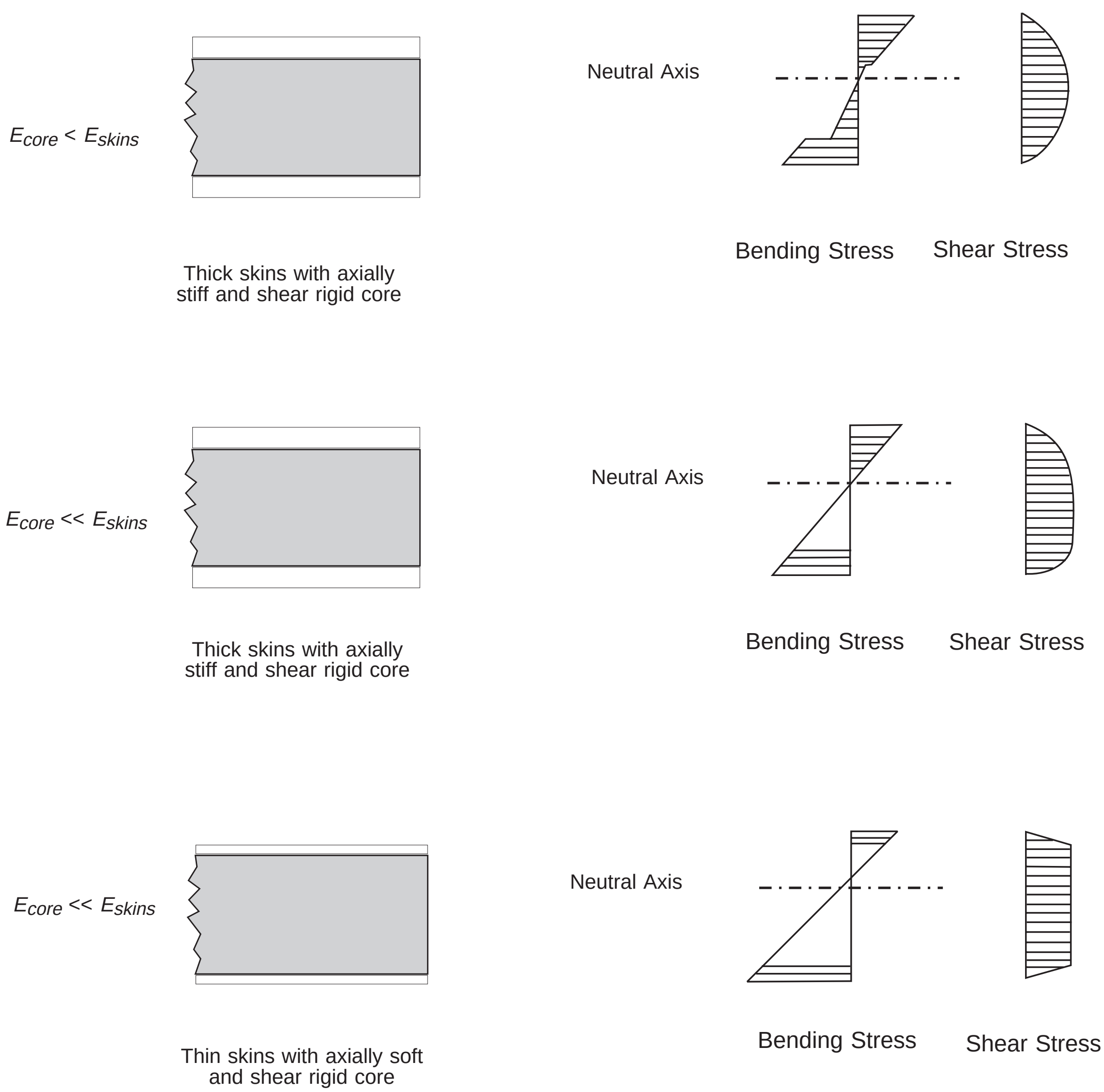


Figure 4-29 Bending and Shear Stress Distribution in Sandwich Beams (2-D) with Relatively Stiff Cores [***Structural Plastics Design Manual*** published by the American Society of Civil Engineers.]

Sandwich Failures with Relatively Soft Cores

Sandwich laminates with soft cores do not behave as beam theory would predict. Because shear loads are not as efficiently transmitted, the skins themselves carry a larger share of the load in bending about their own neutral axis, as shown in Figure 4-30. ASCE [4-34] defines a term for shear flexibility coefficient as:

$$\theta \approx \frac{L}{2}\left[\frac{D_v}{D_{mf}}\right]^{1/2} \qquad (4\text{-}21)$$

where L is the panel span and D_v and D_{mf} are values for shear and bending stiffness, respectively. Figure 4-31 shows the influence of shear flexibility on shear and bending stress distribution for a simply supported beam.

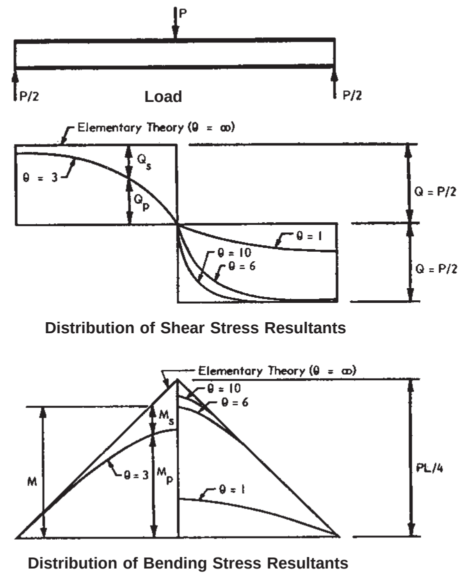


Figure 4-31 Stress Distribution with Flexible Cores [ASCE Manual]

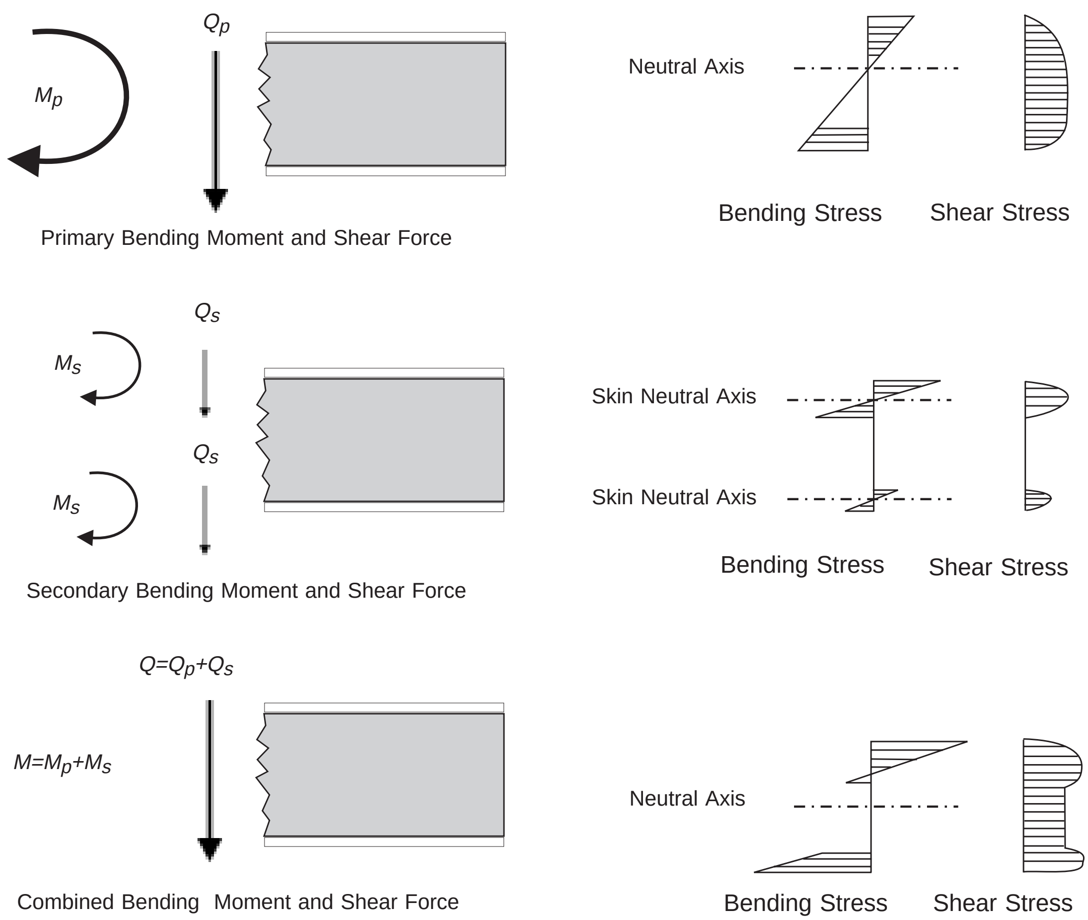


Figure 4-30 Bending and Shear Stress Distribution in Sandwich Beams (2-D) with Relatively Soft Cores [***Structural Plastics Design Manual*** published by the American Society of Civil Engineers.]

First Ply Failure

First ply failure occurs when the first ply or ply group fails in a multidirectional laminate. The load corresponding to this failure can be the design limit load. The total number of plies, the relative stiffnesses of those plies and the overall stress distribution (load sharing) among the plies determines the relationship between first ply failure and last ply (ultimate) failure of the laminate. As an illustration of this concept, consider a structural laminate with a gel coat surface. The surface is typically the highest stressed region of the laminate when subjected to flexural loading, although the gel coat layer will typically have the lowest ultimate elongation within the laminate. Thus, the gel coat layer will fail first, but the load carrying capability of the laminate will remain relatively unchanged.

Strain Limited Failure

The ***ABS Guide for Building and Classing High-Speed Craft*** [4-36] provides guidance on calculating first ply failure based on strain limits. The critical strain of each ply is given as:

$$\varepsilon_{crit} = \frac{\sigma_{ai}}{E_{ai}\left[\,\left|\bar{y} - y_i\right| + \tfrac{1}{2}\,t_i\right]} \qquad (4\text{-}22)$$

where:

σ_{ai} = strength of ply under consideration
= σ_t for a ply in the outer skin
= σ_c for a ply in the inner skin

E_{ai} = modulus of ply under consideration
= E_t for a ply in the outer skin
= E_c for a ply in the inner skin

$\bar{y}$ = distance from the bottom of the panel to the neutral axis

y_i = distance from the bottom of the panel to the ply under consideration

t_i = thickness of ply under consideration

σ_t = tensile strength of the ply being considered

σ_c = compressive strength of the ply being considered

E_t = tensile stiffness of the ply being considered

E_c = compressive stiffness of the ply being considered

Stress Limited Failure

The stress or applied moment that produces failure in the weakest ply is a function of the portion of the overall failure moment carried by the ply that fails, FM_i, defined [4-36] as:

$$FM_i = \varepsilon_{\min} E_{ai} t_i \left(\left|\bar{y} - y_i\right|\right)^2 \qquad (4\text{-}23)$$

where:

$\varepsilon_{\min}$ = the smallest critical strain that is acting on an individual ply

The minimum section moduli for outer and inner skins, respectively, of a sandwich panel based on the failure moment responsible for first ply stress failure is given as:

$$SM_o = \frac{\sum_{i=1}^{n} FM_i}{\sigma_{to}} \qquad (4\text{-}24)$$

$$SM_i = \frac{\sum_{i=1}^{n} FM_i}{\sigma_{ci}} \qquad (4\text{-}25)$$

where:

SM_o = section modulus of outer skin

SM_i = section modulus of inner skin

n = total number of plies in the skin laminate

σ_{to} = tensile strength of outer skin determined from mechanical testing or via calculation of tensile strength using a weighted average of individual plies for preliminary estimations

σ_{ci} = compressive strength of inner skin determined from mechanical testing or via calculation of compressive strength using a weighted average of individual plies for preliminary estimations

Creep

Engineered structures are often required to resist loads over a long period of time. Structures subjected to creep, such as bridges and buildings, are prime examples. Deckhouses and machinery foundations are examples of marine structures subject to long-term stress. Just as many marine composite structural problems are deflection-limited engineering problems, long-term creep characteristics of composite laminates has been an area of concern, especially in way of main propulsion shafting, where alignment is critical. The following discussion on creep is adapted from the ***Structural Plastics Design Manual*** published by the American Society of Civil Engineers. [4-34]

Generalized Creep Behavior

When composite materials are subjected to constant stress, strain in load path areas will increase over time. This is true for both short-term and long-term loading, with the later most often associated with the phenomenon known as creep. With long-term creep, the structural response of an engineering material is often characterized as viscoelastic. Viscoelasticity is defined as a combination of elastic (return to original shape after release of load) and viscous (no return to original shape) behavior. When considering plastics as engineering materials, the concept of viscoelasticity is germane. Loads, material composition, environment, temperature all affect the degree of viscoelasticity or expected system creep. Figure 4-32 presents a long-term overview of viscoelastic modulus for two thermoplastic resin systems and a glass/epoxy thermoset system.

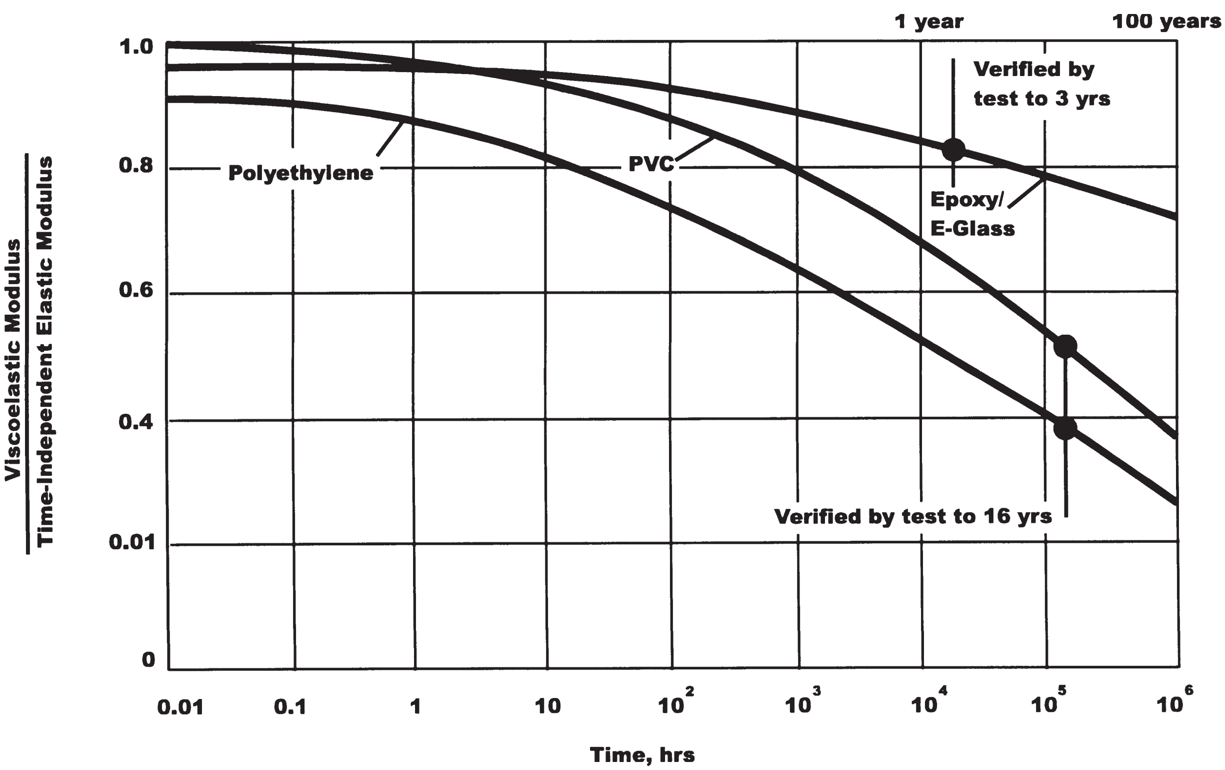


Figure 4-32 Variation in Viscoelastic Modulus with Time [***Structural Plastics Design Manual*** published by the American Society of Civil Engineers]

Composite Material Behavior During Sustained Stress

Creep testing is usually performed in tensile or flexure modes. Some data has been developed for cases of multiaxial tensile stress, which is used to describe the case of pressure vessels and pipes under hydrostatic load. Composite material creep behavior can be represented by plotting strain versus time, usually using a log scale for time. Strain typically shows a steep slope initially that gradually levels off to failure at some time, which is material dependent. Ductile materials will show a rapid increase in strain at some point corresponding to material "yield." This time-dependent yield point is accompanied by crazing, microcracking, stress whitening or complete failure.

Methods for mathematically estimating creep behavior have been developed based on experimentally determined material constants. Findley [4-34] proposed the following equation to describe strain over time for a given material system:

$$\varepsilon = \varepsilon'_0 + \varepsilon'_t \, t^n \tag{4-26}$$

where:

ε = total elastic plus time-dependent strain (inches/inch or mm/mm)

ε'_0 = stress-dependent, time-independent initial elastic strain (inches/inch or mm/mm)

ε'_t = stress-dependent, time-dependent coefficient of time-dependent strain (inches/inch or mm/mm)

n = material constant, substantially independent of stress magnitude

t = time after loading (hours)

When the continuously applied stress, σ, is less than the constants σ_0 and σ_t given in Table 4-7, equation (4-26) can be rewritten as:

$$\varepsilon = \varepsilon_0 \frac{\sigma}{\sigma_0} + \varepsilon_t \, t^n \frac{\sigma}{\sigma_t} \tag{4-27}$$

When E_0, an elastic modulus independent of time is defined as $\frac{\sigma_0}{\varepsilon_0}$ and E_t, a modulus that characterizes time-dependent behavior is defined as $\frac{\sigma_t}{\varepsilon_t}$, equation (4-27) can be given as:

$$\varepsilon = \sigma \left[\frac{1}{E_0} + \frac{t^n}{E_t} \right] \tag{4-28}$$

Constants for the viscoelastic behavior of some engineering polymeric systems are given in Table 4-7. Data in Table 4-7 is obviously limited to a few combinations of reinforcements and resin systems. Indeed, the composition and orientation of reinforcements will influence creep behavior. As composite material systems are increasingly used for infrastructure applications, creep testing of modern material systems should increase.

Table 4-7 Constants for Viscoelastic Equations [*Structural Plastics Design Manual* published by the American Society of Civil Engineers]

Material System	n dimen-sionless	ε_0 ins/in	ε_t ins/in	σ_0 psi	σ_t psi	E_0 10^6 psi	E_t 10^6 psi
Polyester/glass (style 181) - dry	0.090	0.0034	0.00045	15,000	14,000	4.41	31.5
Polyester/glass (style 181) - water immersed	0.210	0.0330	0.00017	80,000	13,000	2.42	76.5
Polyester/glass (style 1000) - dry	0.100	0.0015	0.00022	10,000	8,600	6.67	39.1
Polyester/glass (style 1000) - water immersed	0.190	0.0280	0.00011	80,000	6,500	2.86	60.2
Polyester/glass mat - dry	0.190	0.0067	0.0011	8,500	8,500	1.27	7.73
Polyester/glass woven roving - dry	0.200	0.0180	0.00100	40,000	22,000	2.22	22.0
Epoxy/glass (style 181) - dry	0.160	0.0057	0.00050	25,000	50,000	4.39	100.0
Epoxy/glass (style 181) - water immersed	0.220	0.25	0.00006	80,000	11,000	3.20	200.0
Polyethylene	0.154	0.027	0.0021	585	230	0.0216	0.111
PVC	0.305	0.00833	0.00008	4,640	1,630	0.557	20.5

Performance in Fires

Composite materials based on organic matrices are flammable elements that should be evaluated to determine the potential risk associated with their use. In a fire, general purpose resins will burn off, leaving only the reinforcement, which has no inherent structural strength. “T-vessels” inspected by the U.S. Coast Guard must be fabricated using low flame spread resins. These resins usually have additives such as chlorine, bromine or antimony. Physical properties of the resins are usually reduced when these compounds are added to the formulation. There is also some concern about the toxicity of the gases emitted when these resins are burned.

The fire resistance of individual composite components can be improved if they are coated with intumescent paints (foaming agents that will char and protect the component during minor fires). The designer of commercial vessels is primarily concerned with the following general restrictions (see appropriate Code of Federal Regulation for detail):

- Subchapter T - Small Passenger Vessels: Use of low flame spread (ASTM E 84 <100) resins;
- Subchapter K - Small Passenger Vessels Carrying More Than 150 passengers or with overnight accommodations for 50 - 150 people: must meet SOLAS requirement with hull structure of steel or aluminum conforming to ABS or Lloyd’s (FRP as per *IMO HSC Code*);
- Subchapter I - Cargo Vessels: Use of incombustible materials - construction is to be of steel or other equivalent material; and
- Subchapter H - Passenger Vessels: SOLAS requires noncombustible structural materials or materials insulated with approved noncombustible materials so that the average temperature will not rise above a designated temperature.

Details on SOLAS requirements appear later in this section. The industry is currently in the process of standardizing tests that can quantify the performance of various composite material systems in a fire. The U.S. Navy has taken the lead in an effort to certify materials for use on submarines [4-37]. Table 4-10 presents some composite material test data compiled for the Navy. The relevant properties and associated test methods are outlined in the following topics. No single test method is adequate to evaluate the fire hazard of a particular composite material system. The behavior of a given material system in a fire is dependent not only on the properties of the fuel, but also on the fire environment to which the material system may be exposed. Proposed standardized test methods for flammability and toxicity characteristics cover the spectrum from small-scale to large-scale tests.

Small-Scale Tests

Small-scale tests are quick, repeatable ways to determine the flammability characteristics of organic materials. Usually, a lot of information can be obtained using relatively small test specimens.

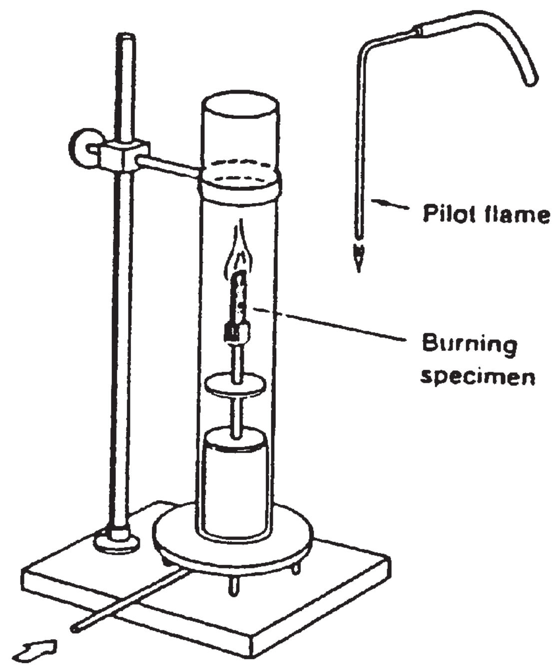


Figure 4-33 Sketch of the Limiting Oxygen Index Apparatus [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

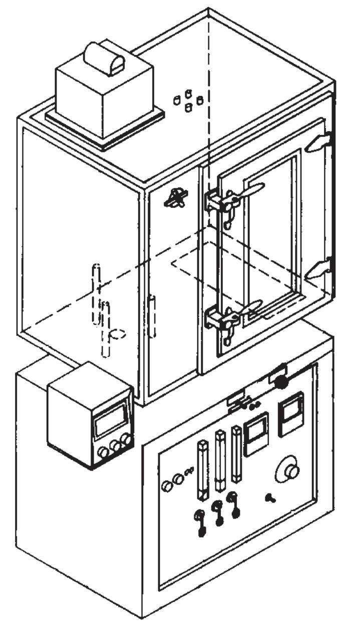


Figure 4-34 Smoke Obscuration Chamber [ASTM E 662]

Oxygen-Temperature Limiting Index (LOI) Test - ASTM D 2863 (Modified)

The Oxygen Temperature Index Profile method determines the minimum oxygen concentration needed to sustain combustion in a material at temperatures from ambient to 570°F. During a fire, the temperature of the materials in a compartment will increase due to radiative and conductive heating. As the temperature of a material increases, the oxygen level required for ignition decreases. This test assesses the relative resistance of the material to ignition over a range of temperatures. The test apparatus is shown in Figure 4-33.

Approximately (40) ¼" to ½" x ⅛" x 6" samples are needed for the test. Test apparatus consists of an Oxygen/Nitrogen mixing system and analysis equipment. The test is good for comparing similar resin systems, but may be misleading when vastly different materials are compared.

N.B.S. Smoke Chamber - ASTM E 662

Figure 4-34 shows a typical NBS Smoke Chamber. This test is used to determine the visual obscuration due to fire. The sample is heated by a small furnace in a large chamber and a photocell arrangement is used to determine the visual obscuration due to smoke from the sample.

The test is performed in flaming and non-flaming modes, requiring a total of (6) 3" x 3" x ⅛" samples. Specific Optical Density, which is a dimensionless number, is recorded. The presence of toxic gases, such as CO, CO_2, HCn and HCl can also be recorded at this time. Table 4-8 shows some typical values recorded using this test.

Table 4-8 Results of Smoke Chamber Tests (E 662) for Several Materials [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

Material	Exposure	Optical Density 20 minutes	Optical Density 5 minutes
Phenolic Composite	Flaming	7	
	Nonflaming	1	
Polyester Composite	Flaming	660	321
	Nonflaming	448	22
Plywood	Flaming	45	
Nylon Carpet	Flaming	270	
Red Oak Flooring	Flaming	300	

Cone Calorimeter - ASTM E 1354

This is an oxygen consumption calorimeter that measures the heat output of a burning sample by determining the amount of oxygen consumed during the burn and calculating the amount of energy involved in the process. The shape of the heating coil resembles a truncated cone. The test apparatus may be configured either vertically or horizontally, as shown in Figure 4-36. The device is used to determine time to ignition, the mass loss of the sample, the sample's heat loss, smoke, and toxic gas generation at a given input heat flux. This is a new test procedure that uses relatively small (4" x 4") test specimens, usually requiring (24) for a full series of tests.

Radiant Panel - ASTM E 162

This test procedure is intended to quantify the surface flammability of a material as a function of flame spread and heat contribution. The ability of a panel to stop the spread of fire and limit heat generated by the material is measured. A 6" x 18" specimen is exposed to heat from a 12" x 18" radiant heater. The specimen is held at a 45° angle, as shown in Figure 4-35.

The test parameters measured include the time required for a flame front to travel down the sample's surface and the temperature rise in the stack. The Flame Spread Index, I_s, is calculated from these factors. This number should not be confused with the *FSI* calculated from the ASTM E 84 test, which utilizes a 25-foot long test chamber. Table 4-9 shows some comparative E 162 data.

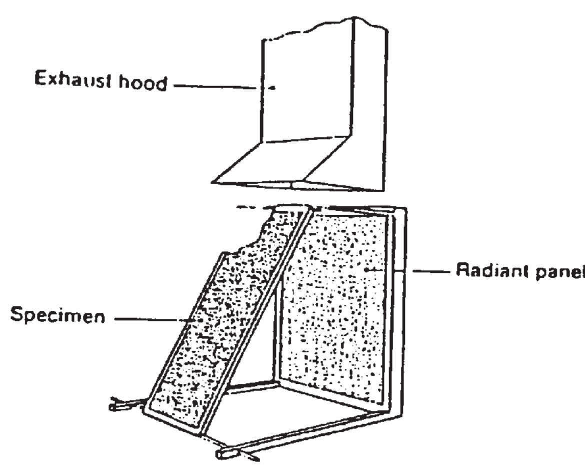


Figure 4-35 Sketch of the NBS Radiant Panel Test Configuration [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

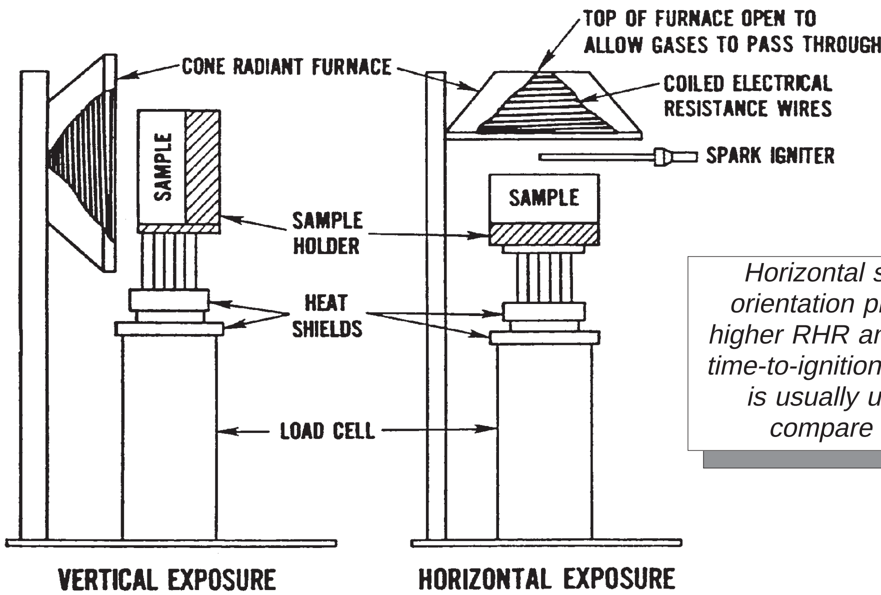


Figure 4-36 Sketch of a Cone Calorimeter [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

Horizontal sample orientation produces higher RHR and shorter time-to-ignition data and is usually used to compare data

Table 4-9 Flame Spread Index as per MIL-STD 2031(SH) (20 max allowable)

Sorathia (1990)	Graphite/Phenolic	**6**
	Graphite/BMI	**12**
	Graphite/Epoxy	**20**
	Glass/Vinylester with Phenolic Skin	**19**
	Glass/Vinylester with Intumescent Coating	38
	Glass/Vinylester	156
Silvergleit (1977)	Glass/Polyester	31 - 39
	Glass/Fire Retardant Polyester	**5** - 22
	Glass/Epoxy	**1** - 45
	Graphite/Epoxy	32
	Graphite/Fire Retardant Epoxy	**9**
	Graphite/Polyimide	**1** - 59
Rollhauser (1991)	Fire Tests of Joiner Bulkhead Panels	
	Nomex® Honeycomb	**19** - 23
	FMI (GRP/Syntactic core)	**2 - 3**
	Large Scale Composite Module Fire Testing	
	All GRP Module	238
	Phenolic-Clad GRP	36

Table 4-10 Heat Release Rates and Ignition Fire Test Data for Composite Materials [Hughes Associates, *Heat Release Rates and Ignition Fire Test Data for Representative Building and Composite Materials*]

Material/Reference		Applied Heat Flux (kW/m²)	Peak HRR (kW/m²)	Average Heat Release Rate - HRR (kW/m²)			Ignition Time
				1 min	2 min	5 min	
Epoxy/fiberglass	A	25,50,75					32,8,5
Epoxy/fiberglass	B	25,50,75					30,8,6
Epoxy/fiberglass 7mm	C	25,50,75	158,271,304				
Epoxy/fiberglass 7mm	D	25,50,75	168,238,279				
Epoxy/fiberglass 7mm	E	26,39,61	100,150,171				
Epoxy/fiberglass 7mm	F	25,37	117,125				
Epoxy/fiberglass 7mm	G	25,50,75	50,154,117				
Epoxy/fiberglass 7mm	H	25,50,75	42,71,71				
Epoxy/fiberglass 7mm	I	35	92				
Phenolic/fiberglass	A	25,50,75					28,8,4
Phenolic/fiberglass	B	25,50,75					NI,8,6
Phenolic/FRP 7mm	C	25,50,75	4,140,204				
Phenolic/FRP 7mm	D	25,50,75	4,121,171				
Phenolic/FRP 7mm	E	26,39,61	154,146,229				
Phenolic/FRP 7mm	F	25,37	4,125				
Phenolic/FRP 7mm	G	25,50,75	4,63,71				
Phenolic/FRP 7mm	H	25,50,75	4,50,63				
Phenolic/FRP 7mm	I	35	58				
Polyester/fiberglass	J	20	138				
FRP	J	20,34,49	40,66,80				
GRP	J	33.5	81				
Epoxy/Kevlar® 7mm	A	25,50,75					33,9,4
Epoxy/Kevlar® 7mm	B	25,50,75					36,7,6
Epoxy/Kevlar® 7mm	C	25,50,75	108,138,200				
Epoxy/Kevlar® 7mm	D	25,50,75	100,125,175				
Epoxy/Kevlar® 7mm	E	26,39,61	113,150,229				
Epoxy/Kevlar® 7mm	F	20,25,27	142,75,133				
Epoxy/Kevlar® 7mm	G	25,50,75	20,83,83				
Epoxy/Kevlar® 7mm	H	25,50,75	20,54,71				
Epoxy/Kevlar® 7mm	I	35	71				
Phenolic/Kevlar® 7mm	A	25,50,75					NI,12,6

Material/Reference		Applied Heat Flux (kW/m^2)	Peak HRR (kW/m^2)	Average Heat Release Rate - HRR (kW/m^2) 1 min	2 min	5 min	Ignition Time
Phenolic/Kevlar® 7mm	B	25,50,75					NI,9,6
Phenolic/Kevlar® 7mm	C	25,50,75	0,242,333				
Phenolic/Kevlar® 7mm	D	25,50,75	0,200,250				
Phenolic/Kevlar® 7mm	E	26,39,64	100,217,300				
Phenolic/Kevlar® 7mm	F	30,37	147,125				
Phenolic/Kevlar® 7mm	G	25,50,75	13,92,117				
Phenolic/Kevlar® 7mm	H	25,50,75	13,75,92				
Phenolic/Kevlar® 7mm	I	35	83				
Phenolic/Graphite 7mm	C	25,50,75	4,183,233				
Phenolic/Graphite 7mm	D	25,50,75	0,196,200				
Phenolic/Graphite 7mm	E	39,61	138,200				
Phenolic/Graphite 7mm	F	20,30,37	63,100,142				
Phenolic/Graphite 7mm	G	25,50,75	13,75,108				
Phenolic/Graphite 7mm	H	25,50,75	13,63,88				
Phenolic/Graphite 7mm	I	35	71				
Phenolic/Graphite 7mm	A	25,50,75					NI,12,6
Phenolic/Graphite 7mm	B	25,50,75					NI,10,6
Epoxy	K	35,50,75		150,185,210	155,170,190	75,85,100	116,76,40
Epoxy/Nextel-Prepreg	K	35,50,75		215,235,255	195,205,240	95,105,140	107,62,31
Bismaleimide (BMI)	K	35,50,75		105,120,140	130,145,170	105,110,125	211,126,54
BMI/Nextel-Prepreg	K	35,50,75		100,120,165	125,135,280	120,125,130	174,102,57
BMI/Nextel-Dry	K	35,50,75		145,140,150	150,150,165	110,120,125	196,115,52
Koppers 6692T	L	25,50,75					263,60,21
Koppers 6692T/FRP	L	25,35,35	59,NR,101	50,55,70	40,65,55	25,65,40	
Koppers 6692T/FRP	L	50,50,75	85,NR,100	60,60,80	50,45,80	40,35,60	
Koppers Iso/FRP	L	50		215	180	150	55
Koppers Iso/Bi Ply	L	50		210	75	145	50
Koppers Iso/FRP	L	50		235	190	160	45
Koppers Iso/mat/WR	L	50		135	115	100	35
Koppers Iso/S2WR	L	50		130	110	0	45
Dow Derakane 3mm	L	35,50,75					
Dow Derakane 25mm	L	35,50,75					
Dow Vinylester/FRP	L	35,50,50		295,225,190	255,195,170	180,145,160	
Dow Vinylester/FRP	L	75,75,75		240,217,240	225,205,225	185,165,185	

Material/Reference		Applied Heat Flux (kW/m^2)	Peak HRR (kW/m^2)	Average Heat Release Rate - HRR (kW/m^2)			Ignition Time
				1 min	2 min	5 min	
Lab Epoxy 3mm	LL	35,50,75					116,76,40
Lab Epoxy/Graphite	L	35,50,75		150,185,210	155,170,190	75,85,100	
Lab BMI 3mm	L	35,50,75					211,126,54
Lab BMI/Graphite	L	35,50,75		105,120,140	130,145,170	105,110,125	
Glass/Vinylester	M	25,75,100	377,498,557	290,240,330		180,220,—	281,22,11
Graphite/Epoxy	M	25,75,100	0,197,241	0,160,160		0,90,—	NI,53,28
Graphite/BMI	M	25,75,100	0,172,168	0,110,130		0,130,130	NI,66,37
Graphite/Phenolic	M	25,75,100	0,159,—	0,80,—		0,80,—	NI,79,—

Designation	Furnace	Reference
A	Cone - H	Babrauskas, V. and Parker, W.J., "Ignitability Measurements with the Cone Calorimeter," Fire and Materials, Vol. 11, 1987, pp. 31-43.
B	Cone - V	
C	Cone - V	Babrauskas, V., "Comparative Rates of Heat Release from Five Different Types of Test Apparatuses," Journal of Fire Sciences, Vol. 4, March/April 1986, pp. 148-159.
D	Cone - H	
E	FMRC - H	
F	Flame Height - V	
G	OSU/02 - V	
H	OSU - V (a)	
I	OSU - V (b)	
J	OSU - V	Smith, E.E., "Transit Vehicle Material Specification Using Release Rate Tests for Flammability and Smoke,"Report No. IH-5-76-1, American Public Transit Association, Washington, DC, Oct. 1976.
K	Cone	Brown, J . E ., "Combustion Characteristics of Fiber Reinforced Resin Panels," Report No. FR3970, U.S.Department of Commerce, N.B.S., April 1987.
L	Cone	Brown, J . E ., Braun, E. and Twilley, W.H., "Cone Calorimeter Evaluation of the Flammability of Composite Materials," US Department of the Navy, NAVSEA 05R25,Washington, DC, Feb. 1988.
M	Cone	Sorathia, U., "Survey of Resin Matrices for Integrated Deckhouse Technology," DTRC SME-88-52, David Taylor Research Center, August 1988.
H = horizontal		
V = vertical		
NI = not ignited		
(a) = initial test procedure		
(b) = revised test procedure		

Intermediate-Scale Tests

Intermediate-scale tests help span the gap between the uncertainties associated with small scale tests and the cost of full scale testing. Tests used by the U.S. Navy and the U.S. Coast Guard are described in the following.

DTRC Burn Through Test

This test determines the time required to burn through materials subjected to 2000°F under a controlled laboratory fire condition. This is a temperature that may result from fluid hydrocarbon fueled fires and can simulate the ability of a material to contain such a fire to a compartment. Figure 4-37 shows the arrangement of specimen and flame source for this test. (2) 24" x 24" samples are needed for this test. Burn through times for selected materials is presented in Table 4-11.

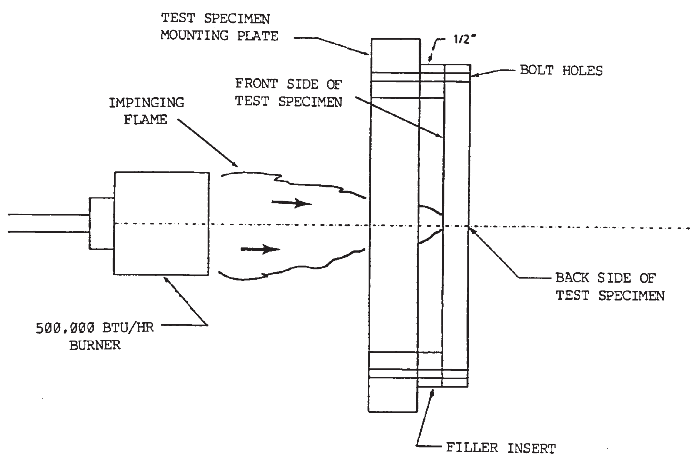
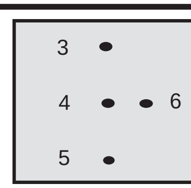


Figure 4-37 Sketch of the DTRC Burn Through Sample and Holder [Rollhauser, *Fire Tests of Joiner Bulkhead Panels]*

Table 4-11 DTRC Burn Through Times for Selected Materials [Rollhauser, *Fire Tests of Joiner Bulkhead Panels*]

Sample	Burn Through Time	Maximum Temperatures, °F, at Locations on Panel, as Indicated at Right 			
	Min:Sec	T3	T4	T5	T6
Plywood 1	5:00	300	425	150	125
	4:45	1150	1000	200	1100
Plywood 2	2:40	900	1000	200	200
	2:45	350	100	100	100
Polyester Composite	26:00	not recorded			
	30:00				
Phenolic Composite	>60:00				
Aluminum, ¼"	2:35	450	2000	600	100
	2:05	525	2000	600	200

ASTM E 1317-90, Standard Test Method for Flammability of Marine Finishes

A description and background contained in the test standard provide insight as to why this test may be appropriate for intermediate-scale evaluation of shipboard composite material systems. The test method describes a procedure for measuring fire properties associated with flammable surfaces finishes used on noncombustible substrates aboard ships. The International Safety of Life at Sea (SOLAS) Convention requires the use of marine finishes of limited flame spread characteristics in commercial vessel construction.

Figure 4-38 shows the overall LIFT apparatus geometry, including test specimen and radiant heater. Figure 4-39 shows an E-glass/vinyl ester panel during a test

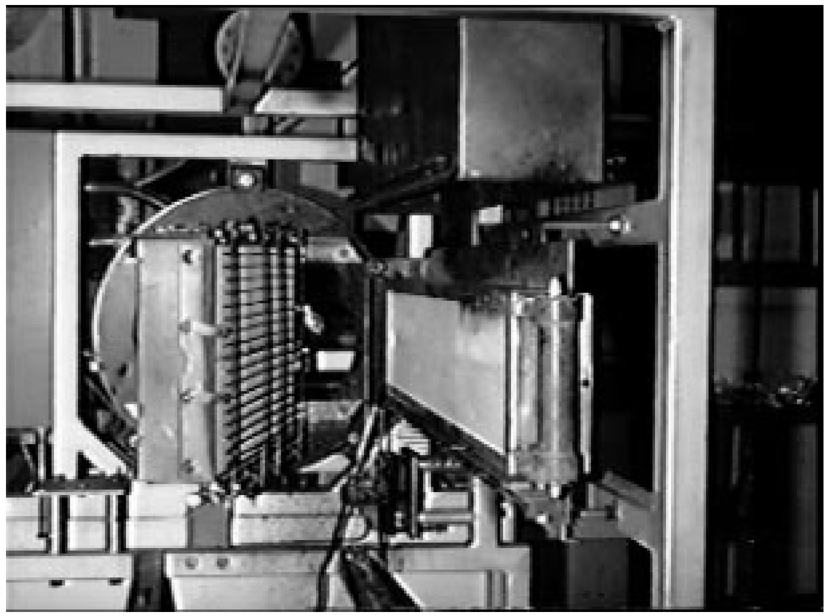


Figure 4-38 LIFT Apparatus Geometry

The increased understanding of the behavior of unwanted fires has made it clear that flame spread alone does not adequately characterize fire behavior. It is also important to have other information, including ease of ignition and measured heat release during a fire exposure. The International Maritime Organization (IMO) has adopted a test method, known as IMO Resolution A.564(14), which is essentially the same as the ASTM test method [4-38].

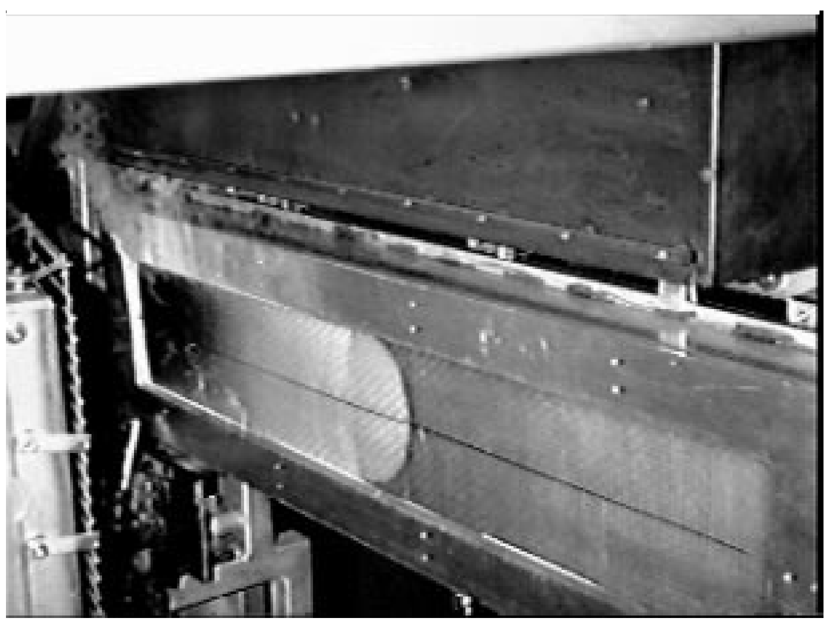


Figure 4-39 LIFT Test Panel at the Time of Ignition

The test equipment used by this test method was initially developed for the IMO to meet the need for defining low flame spread requirements called for by the Safety of Life at Sea (SOLAS) Convention. The need was emphasized when the IMO decided that noncombustible bulkhead construction would be required for all passenger vessels. These bulkheads were usually faced with decorative veneers.

Some of the decorative veneers used on these bulkheads had proved to be highly flammable during fires. Various national flammability test methods were considered. Development of an International Standards Organization (ISO) test method also was considered. Since it became apparent that development of a suitable test by ISO/TC92 would require more time than IMO had envisioned, IMO decided during 1976-1977 to accept an offer from the United States delegation to develop a suitable prototype test. Initial work on the test method was jointly sponsored by the National Institute of Standards and Technology (NIST), then the National Bureau of Standards (NBS), and the United States Coast Guard.

The data presented for several marine "coverings" in Figure 4-40 shows flux at "flame front" as a function "flame arrival time." The dotted lines represent "heat for sustained burning." In general, materials of higher heat of sustained burning and especially those also accompanied with higher critical flux at extinguishment are significantly safer materials with respect to flame spread behavior than the others shown. [4-38]

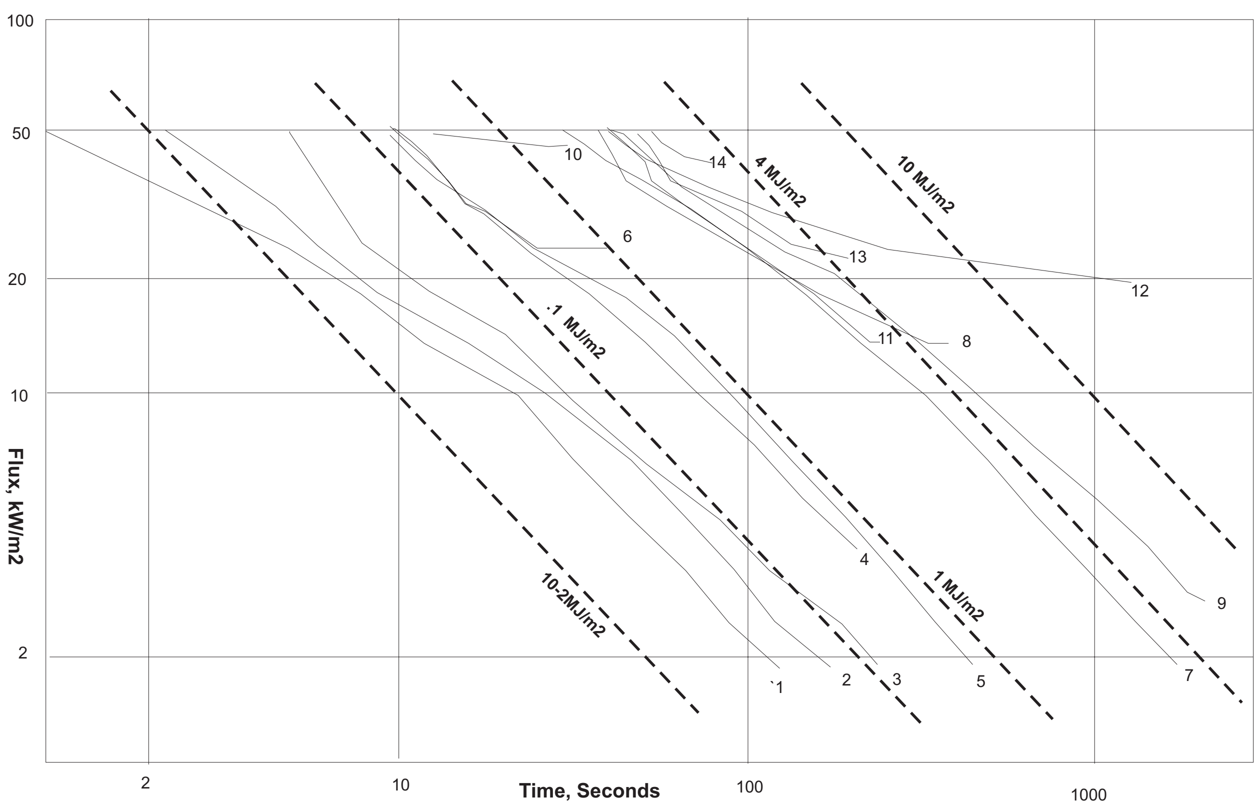


Figure 4-40 ASTM E 1317 Flame Front Flux versus Time for:

1 GM 21, PU Foam, PC
2 GM 21, F.R. PU Foam, PCF
3 FAA Foam 0.95 kg/m2
4 Acrylic Carpet 2.7 kg/m2
5 Fiberboard, unfinished 3.3 kg/m2
6 Wool Carpet 2.4 kg/m2
7 Hardboard, unfinished 3.3 kg/m2
8 Fiberboard, F.R. Paint 3.6 kg/m2
9 Fiberboard, unfinished 5.7 kg/ms
10 Marine Veneer, Sweden
11 Gypsum Board, unfinished
12 Hardboard F.R. Paint 8.5 kg/m2
13 Marine Veneer, Sweden
14 Gypsum Board F.R. Paint

The objectives in developing this test method were as follows:

- To provide a test method for selection of materials of limited flammability; and
- To provide a test method capable of measuring a number of material fire properties in as specified a fashion as possible with a single specimen exposure.

It was recognized that there may be several different ways in which these measurements could be utilized. It was suggested that IMO should use the test as a go/no go measuring tool for surface finish materials to limit the severity of their participation in a fire. The fire research community is interested in variable irradiance ignition measurements, coupled with flame spread measurements to derive more basic fire thermal properties of the materials studied. The National Institute of Standards and Technology (NIST) is continuing its research on the correlation of LIFT results with full-scale testing of composite materials under a cooperative research agreement with Structural Composites.

U.S. Navy Quarter Scale Room Fire Test

This test determines the flashover potential of materials in a room when subjected to fire exposure. The test reduces the cost and time associated with full-scale testing. A 10' x 10' x 8' room with a 30" x 80" doorway is modeled. (1) 36" x 36" and (3) 36" x 30" test material samples are required.

3-Foot E 119 Test with Multiplane Load

In the U.S., the ASTM E 119 test is the generally accepted standard method for evaluating and rating the fire resistance of structural-type building fire barriers. The method involves furnace-fire exposure of a portion of a full-scale fire barrier specimen. The furnace-fire environment follows a monotonically-increasing, temperature-time history, which is specified in the test method document as the standard ASTM E 119 fire. The test method specifies explicit acceptance criteria that involve the measured response of the barrier test specimen at the time into the standard fire exposure, referred to as the fire resistance of the barrier design, that corresponds to the desired barrier rating. For example, a barrier design is said to have a three-hour fire-resistance rating if the tested specimen meets specified acceptance criteria during at least three hours of a standard fire exposure. The fire-resistance rating, in turn, qualifies the barrier design for certain uses. Here the term “qualifies” is intended to mean that the barrier design meets or exceeds the fire-resistance requirements of a building code or other regulation.

U.S. Coast Guard regulations for fire protection and the International Conventions for Safety of Life at Sea of 1948, 1960 and 1974, require that the basic structure of most vessels be of steel or “material equivalent to steel at the end of the applicable fire exposure.” The ASTM E 119 fire curve is used as the applicable fire exposure for rating SOLAS decks and bulkheads. These provisions place the burden of proving equivalency on designers who use noncombustible materials other than steel, where structural fire provisions apply. The 1974 SNAME T&R Bulletin 2-21 [4-39] provides Aluminum Fire Protection Guidelines to achieve these goals for aluminum.

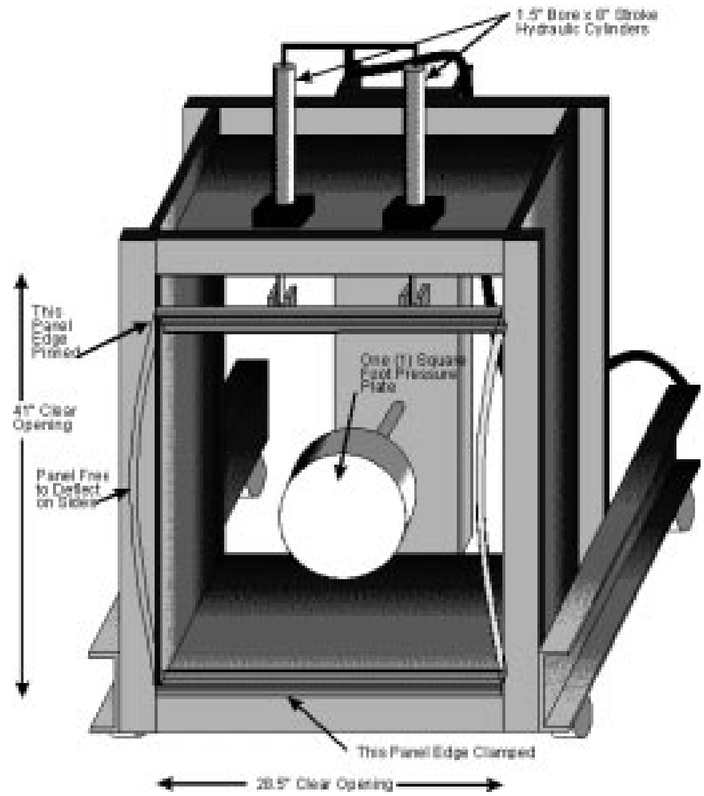


Figure 4-41 Geometry of E 119 Multiplane Load Jig

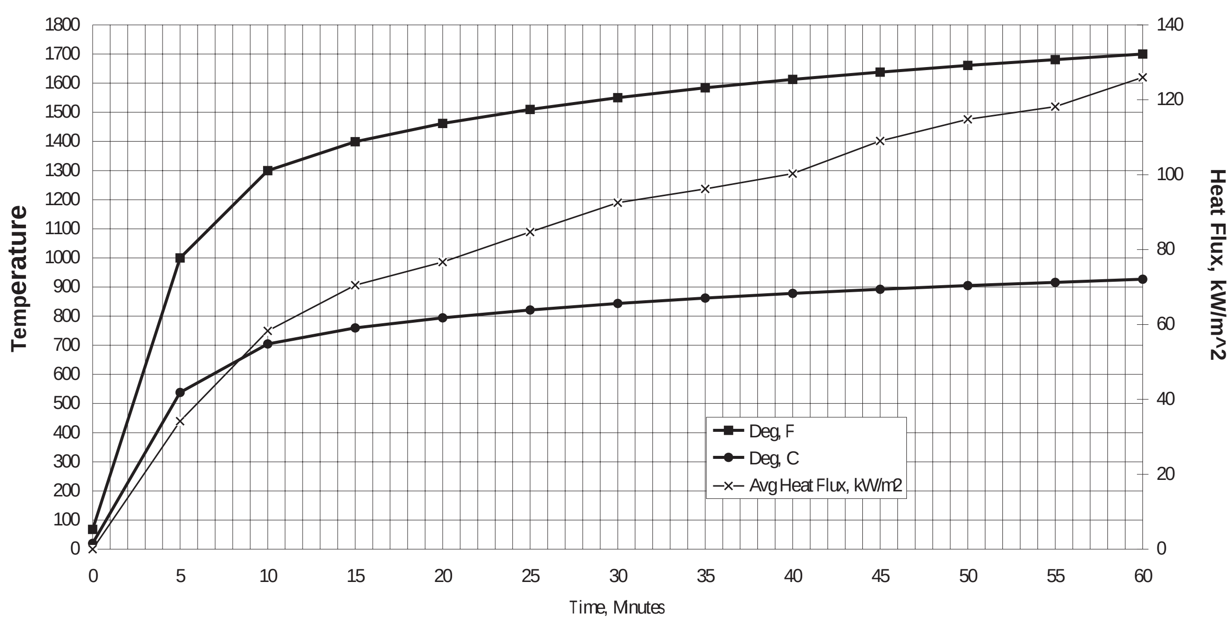


Figure 4-42 Heat Flux from 3-foot Furnace at VTEC Laboratories using the E 119 (SOLAS) Time/Temperature Curve

Figure 4-41 shows the geometry of the multiplane load jig developed by Structural Composites to be used with an E 119 fire exposure. A heat flux map of the 3-foot furnace used for E 119 type testing at VTEC is presented in Figure 4-42. Results from an extensive SBIR research project [4-40] that utilized the multiplane load jig are presented at the end of this section.

Large-Scale Tests

These tests are designed to be the most realistic simulation of a shipboard fire scenario. Tests are generally not standardized and instead are designed to compare several material systems for a specific application. The goal of these tests is to model materials, geometry and the fire threat associated with a specific compartment. The U.S. Navy has standardized parameters for several of their full-scale tests.

Corner Tests

Corner tests are used to observe flame spread, structural response and fire extinguishment of the tested materials. This test was used by the U.S. Navy to test joiner systems. The geometry of the inside corner creates what might be a worst case scenario where the draft from each wall converges. 7-foot high by 4-foot wide panels are joined with whatever connecting system is part of the joinery. Approximately two gallons of hexane fuel is used as the source fire burning in a 1-foot by 1-foot pan [4-37].

Room Tests

This type of test is obviously the most costly and time consuming procedure. Approximately 98 square feet of material is required to construct an 8-foot by 6-foot room. Parameters measured include: temperature evolution, smoke emission, structural response, flame spread and heat penetration through walls. Instrumentation includes: thermocouples and temperatures recorders, thermal imaging video cameras and regular video cameras [4-37].

Summary of MIL-STD-2031 (SH) Requirements

The requirements of MIL-STD-2031 (SH), "*Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems used in Hull, Machinery, and Structural Applications inside Naval Submarines*" [4-37] are summarized here. The foreword of the standard states:

> "The purpose of this standard is to establish the fire and toxicity test methods, requirements and the qualification procedure for composite material systems to allow their use in hull, machinery, and structural applications inside naval submarines. This standard is needed to evaluate composite material systems not previously used for these applications."

Table 4-12 summarizes the requirements outlined in the new military standard. It should be noted that to date, no polymer-based systems have been shown to meet all the criteria of MIL-STD-2031 (SH).

Table 4-12 General Requirements of MIL-STD-2031 (SH), ***Fire and Toxicity Test Methods and Qualification Procedure for Composite Material Systems Used in Hull, Machinery and Structural Applications Inside Naval Submarines***

Fire Test/Characteristic		Requirement		Test Method
Oxygen-Temperature Index (%)	The minimum concentration of oxygen in a flowing oxygen nitrogen mixture capable of supporting flaming combustion of a material.		**Minimum**	ASTM D 2863 (modified)
		% oxygen @ 25°C	35	
		% oxygen @ 75°C	30	
		% oxygen @ 300°C	21	
Flame Spread Index	A number or classification indicating a comparative measure derived from observations made during the progress of the boundary of a zone of flame under defined test conditions.		**Maximum** 20	ASTM E 162
Ignitability (seconds)	The ease of ignition, as measured by the time to ignite in seconds, at a specified heat flux with a pilot flame.		**Minimum**	ASTM E 1354
		100 kW/m^2 Flux	60	
		75 kW/m^2 Flux	90	
		50 kW/m^2 Flux	150	
		25 kW/m^2 Flux	300	
Heat Release Rate (kW/m^2)	Heat produced by a material, expressed per unit of exposed area, per unit of time.		**Maximum**	ASTM E 1354
		100 kW/m^2 Flux		
		Peak	150	
		Average 300 secs	120	
		75 kW/m^2 Flux		
		Peak	100	
		Average 300 secs	100	
		50 kW/m^2 Flux		
		Peak	65	
		Average 300 secs	50	
		25 kW/m^2 Flux		
		Peak	50	
		Average 300 secs	50	
Smoke Obscuration	Reduction of light transmission by smoke as measured by light attenuation.		**Maximum**	ASTM E 662
		D_s during 300 secs	100	
		D_{max} occurrence	240 secs	

Fire Test/Characteristic		Requirement	Test Method
Combustion Gas Generation	Rate of production of combustion gases (e.g. CO, CO_2, HCl, HCn, NO_x, SO_x, halogen, acid gases and total hydrocarbons.	25 kW/m^2 Flux **Maximum** CO 200 ppm CO_2 4% (vol) HCn 30 ppm HCl 100 ppm	ASTM E 1354
Burn Through Fire Test	Test method to determine the time for a flame to burn through a composite material system under controlled fire exposure conditions.	No burn through in 30 minutes	DTRC Burn Through Fire Test
Quarter Scale Fire Test	Test method to determine the flashover potential of materials in a room when subjected to a fire exposure.	No flashover in 10 minutes	Navy Procedure
Large Scale Open Environment Test	Method to test materials at full size of their intended application under controlled fire exposure to determine fire tolerance and ease of extinguishment.	Pass	Navy Procedure
Large Scale Pressurable Fire Test	Method to test materials using an enclosed compartment in a simulated environment under a controlled fire exposure.	Pass	Navy Procedure
N-Gas Model Toxicity Screening	Test method to determine the potential toxic effects of combustion products (smoke and fire gases) using laboratory rats.	Pass	Navy Procedure

Review of SOLAS Requirements for Structural Materials in Fires

SOLAS is the standard that all passenger ships built or converted after 1984 must meet. Chapter II-2 *Fire Protection, Fire Detection and Fire Extinction* defines minimum fire standards for the industry. SOLAS defines three types of class divisions (space defined by decks and bulkheads) that require different levels of fire protection, detection and extinction. Each class division is measured against a standard fire test. This test is one in which specimens of the relevant bulkheads or decks are exposed in a fire test furnace to temperatures corresponding approximately to the *Standard Time-Temperature Curve* of ASTM E 119, which is shown in Figure 4-43 along with other standards. The standard time-temperature curve for SOLAS is developed by a smooth curve drawn through the following temperature points measured above the initial furnace temperature:

- at the end of the first 5 minutes 556°C (1032°F)
- at the end of the first 10 minutes 659°C (1218°F)
- at the end of the first 15 minutes 718°C (1324°F)
- at the end of the first 30 minutes 821°C (1509°F)
- at the end of the first 60 minutes 925°C (1697°F)

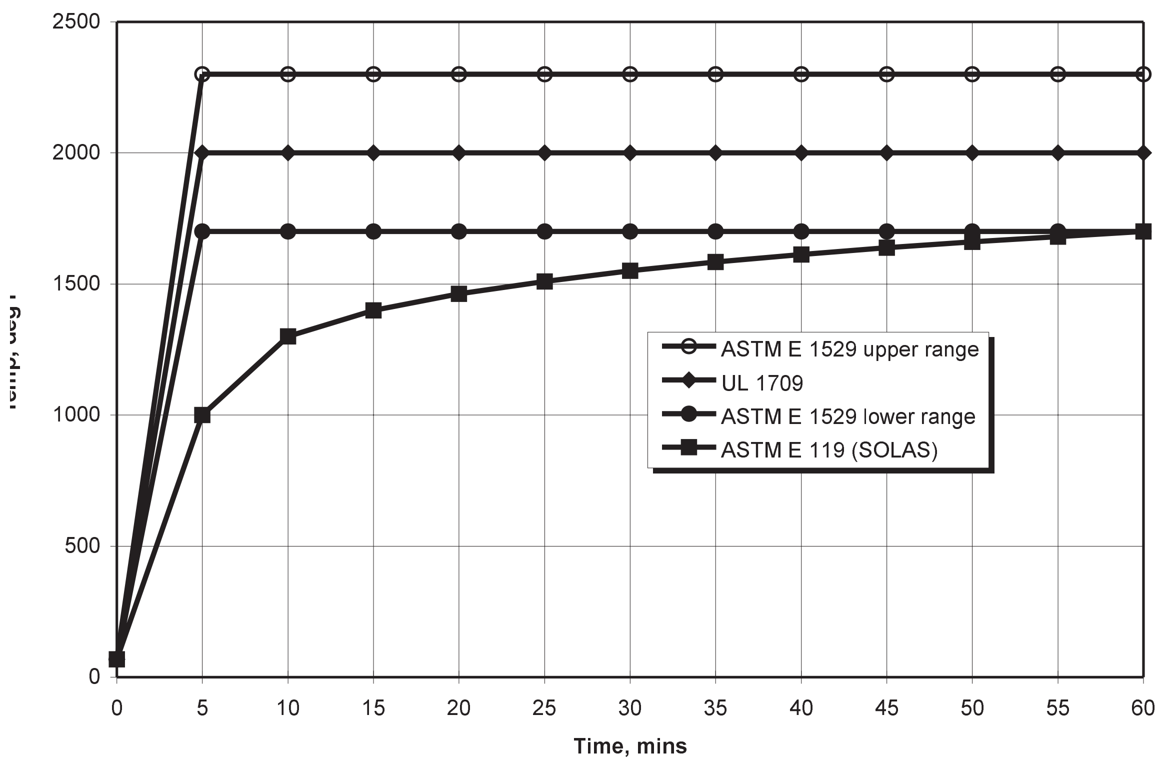


Figure 4-43 Comparison of Three Fire Tests [Rollhauser, *Integrated Technology Deckhouse*]

Noncombustible materials are identified for use in construction and insulation of all SOLAS class divisions. Noncombustible material is a material which neither burns nor gives off flammable vapors in sufficient quantity for self-ignition when heated to approximately 750°C (1382°F), this being determined to the satisfaction of the administration (IMO or USCG) by an established test procedure. Any other material is a combustible material.

Class divisions are “A”, “B,” and “C.” “A” class divisions are bulkheads and decks which:

a. shall be constructed of steel or other equivalent material;

b. shall be suitably stiffened;

c. shall be so constructed as to be capable of preventing the passage of smoke and flame to the end of the one-hour standard fire test; and

d. shall be insulated with approved noncombustible materials such that the average temperature of the unexposed side will not rise more than 139°C (282°F) above the original temperature, nor will the temperature, at any one point, including any joint, rise more than 180°C (356°F) above the original temperature, within the time listed below:

- Class “A-60” = 60 minutes
- Class “A-30” = 30 minutes
- Class “A-15” = 15 minutes
- Class “A-0” = 0 minutes

“B” class divisions are those divisions formed by bulkheads, decks, ceilings or linings and:

a. shall be constructed as to be capable of preventing the passage of smoke and flame to the end of the first half hour standard fire tests;

b. shall have an insulation value such that the average temperature of the unexposed side will not rise more than 139°C (282°F) above the original temperature, nor will the temperature at any point, including any joint, rise more than 225°C (437°F) above the original temperature, within the time listed below:

- Class “B-15” = 15 minutes
- Class “B-0” = 0 minutes

c. they shall be constructed of approved noncombustible materials and all materials entering into the construction and erection of “B” class divisions shall be noncombustible, with the exception that combustible veneers may be permitted provided they meet flammability requirements (ASTM E 1317).

“C” divisions shall be constructed of noncombustible material

Naval Surface Ship Fire Threat Scenarios

The fire threat on surface ships may be self inflicted during peacetime operations or can be the result of enemy action. The later case is generally much more severe, although the database on recent Navy experience deals almost exclusively with events in the former category. Some fire source data suitable for comparing surface ships to submarines is presented in Table 4-13. For both types of combatants, about two-thirds of all fires occur in port or at a shipyard during overhaul.

Table 4-13 Fire Source Data for Naval Combatants

FIRE SOURCE	Surface Ships[1] 1983 - 1987		Submarines[2] 1980 - 1985	
	Number	Percent	Number	Percent
Electrical	285	39%	100	61%
Open Flame/Welding	141	19%	23	14%
Flammable Liquid/Gas	0	0%	13	8%
Radiant Heat	102	14%	8	5%
Matches/Smoking	40	5%	1	1%
Explosion	7	1%	1	1%
Other	89	12%	0	0%
Unknown	68	9%	18	11%
TOTAL:	732	100%	164	100%

[1]Navy Safety Center Database, Report 5102.2
[2]NAVSEA Contract N00024-25-C-2128, "Fire Protection Study," Newport News Shipbuilding

Fires onboard surface ships are usually classified by the severity of a time/temperature profile. Fire scientists like to quantify the size of a fire in terms of heat flux (kW). The following is a rough relationship between fire type and size:

- Small smoldering fire: 2 - 10 kW
- Trash can fire: 10 - 50 kW
- Room fire: 50 - 100 kW
- Post-flashover fire: > 100 kW

A post-flashover fire would represent an event such as the incident on the ***USS Stark***, where Exocet missile fuel ignited in the space.

From the non-combat data presented in Table 4-13, it should be noted that 90% of the reported fires were contained to the general area in which they were started. 75% of the fires were extinguished in under 30 minutes. Most fires occurred in engineering spaces.

Table 4-14 Relative Merit of Candidate Resin Systems for Elevated Temperatures

Resin System		Properties	Price Range $/lb	Room Temp Strength	High Temp Strength	Rate of Heat Release	Smoke & Toxicity
Theremoset	Polyester	Polyester resins are the most common resins used in the marine industry because of their low cost and ease of manufacture. Isophthalic polyesters have better mechanical properties and show better chemical and moisture resistance than ortho polyester	.66 - .95	1	1	1	2
	Epoxy	Excellent mechanical properties, dimensional stability and chemical resistance (especially to alkalis): low water absorption; self-extinguishing (when halogenated); low shrinkage; good abrasion resistance; very good adhesion properties	2.00 - 10.00	3	1	1	1
	Vinyl Ester	Good mechanical, electrical and chemical resistance properties; excellent moisture resistance; intermediate shrinkage	1.30 - 1.75	2	1	1	1
	Phenolic	Good acid resistance; good electrical properties (except arc resistance); high heat resistance	.60 - 5.00	1	2	2	3
	Bismaleimides	Intermediate in temperature capability between epoxy and polyimide; possible void-free parts (no reaction by-product); brittle	10.00 - 25.00	1	3	2	2
	Polyimides	Resistant to elevated temperatures; brittle; high glass transition temperature; difficult to process	22.00	3	3	2	2
Thermoplastic	Polyether Ether Ketone (PEEK)	Good hot/wet resistance, impact resistant; rapid, automated processing possible	21.50 - 28.00	2	2	2	2
	Poly Phenylene Sulfide (PPS)	Good flame resistance and dimensional stability; rapid, automated processing possible	2.00 - 6.00	1	2	3	3
	Poly Ether Sulfone (PES)	Easy processability; good chemical resistance; good hydrolytic properties	4.40 - 7.00	2	1	3	3
	Poly Aryl Sulfone (PAS)	High mechanical properties; good heat resistance; long term thermal stability; good ductility and toughness.	3.55 - 4.25	2	2	3	2

Legend

1 poor
2 moderate
3 good

International Maritime Organization (IMO) Tests

IMO Resolution MSC 40(64) outlines the standard for qualifying marine materials for high speed craft as fire-restricting. This applies to all hull, superstructure, structural bulkheads, decks, deckhouses and pillars. Areas of major and moderate fire hazard must also comply with a SOLAS-type furnace test (MSC.45(65)) with loads, which is similar to ASTM E 119.

IMO Resolution MSC 40(64) on ISO 9705 Test

Tests should be performed according to the standard ISO 9705 Room/Corner Test. This standard gives alternatives for choice of ignition source and sampling mounting technique. For the purpose of testing products to be qualified as "fire restricting materials" under the IMO High-Speed Craft Code, the following should apply:

- Ignition source: Standard ignition source according to Annex A in ISO 9705, i.e. 100 kW heat output for 10 minutes and thereafter 300 kW heat output for another 10 min. Total testing time is 20 minutes; and
- Specimen mounting: Standard specimen mounting, i.e. the product is mounted both on walls and ceiling of the test room. The product should be tested complying to end use conditions.

Calculation of the Parameters Called for in the Criteria

The maximum value of smoke production rate at the start and end of the test should be calculated as follows: For the first 30 seconds of testing, use values prior to ignition of the ignition source, i.e., zero rate of smoke production, when calculating average. For the last 30 seconds of testing use the measured value at 20 minutes, assign that to another 30 seconds up to 20 minutes and 30 seconds and calculate the average. The maximum heat release rate (HRR) should be calculated at the start and the end of the test using the same principle as for averaging the smoke production rate. The time averages of smoke production rate and HRR should be calculated using actual measured values that are not already averaged, as described above.

Criteria for Qualifying Products as "Fire Restricting Materials"

- The time average of HRR excluding the ignition source does not exceed 100 kW;
- The maximum HRR excluding the HRR from the ignition source does not exceed 500 kW averaged over any 30 second period of the test;
- The time average of the smoke production rate does not exceed 1.4 m^2/s;
- The maximum value of smoke production rate does not exceed 8.3m^2/s averaged over any period of 60 seconds during the test;
- Flame spread must not reach any further down the walls of the test room than 0.5 m from the floor excluding the area which is within 1.2 meter from the corner where the ignition source is located; and
- No flaming drops or debris of the test sample may reach the floor of the test room outside the area which is within 1.2 meter from the corner where the ignition source is located

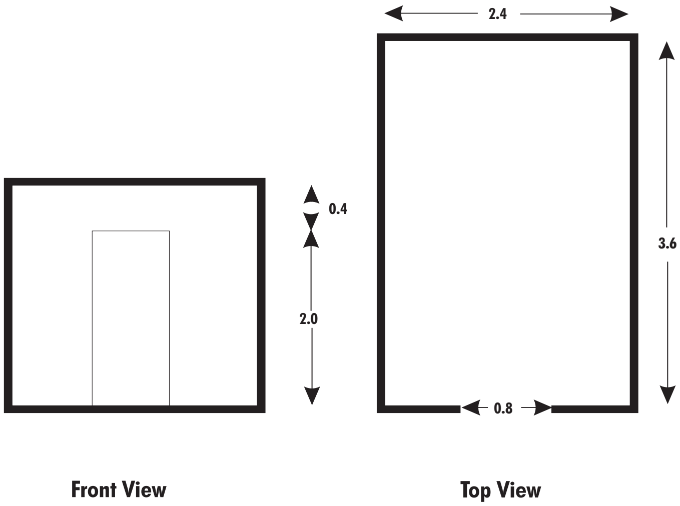


Figure 4-44 Fire Test Room Dimensions (in Meters) for ISO 9705 Test

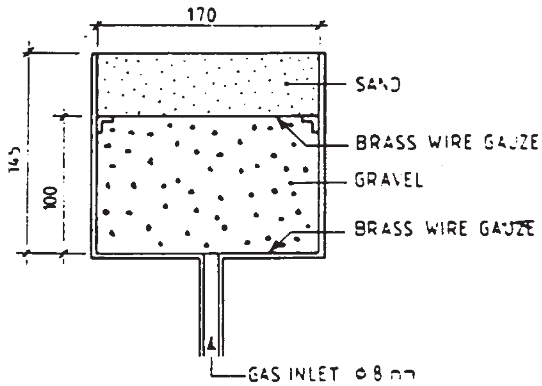


Figure 4-45 Geometry of Sand Burner Used for ISO 9705 Test (dimensions in mm)

References: International Standard ISO/DIS 9705, *Fire Tests - Full Scale Room Test for Surface Products*, available from ANSI, 11 West 42nd Street, New York, NY 10036.

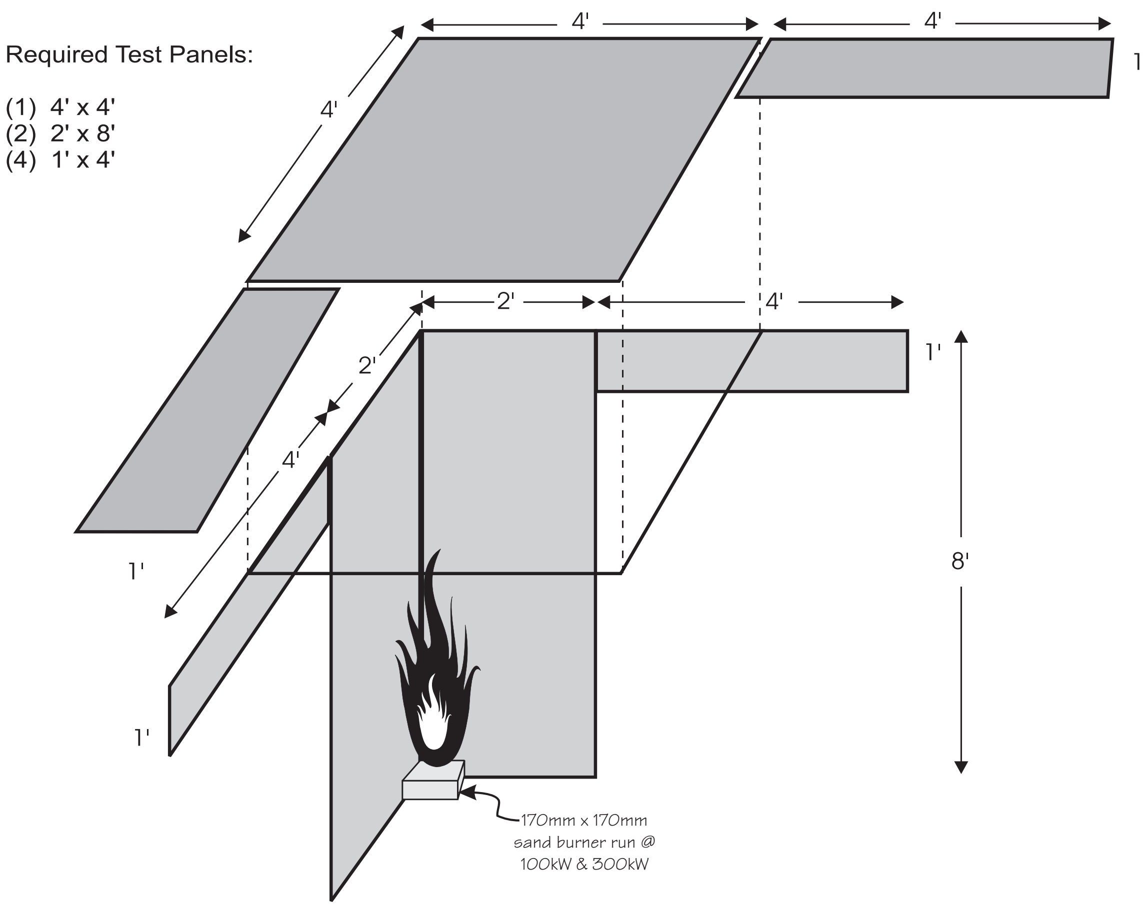


Figure 4-46 Coverage for Modified ISO 9705 Test Using (2) 4' x 8' Sheets of Material

Figure 4-47 ISO 9705-Type Test with Reduced Material Quantities at VTEC Laboratories Showing 300 kW Burner Output [author photo]

Thermo-Mechanical Performance of Marine Composite Materials

The main testing undertaken under a Navy-sponsored SBIR Program [4-40] involved the thermo-mechanical characterization of panels made from typical composite materials used in advanced marine construction. The following describes how the test procedure evolved and what types of panels were tested to verify the methodology.

Fire Insult

The time/temperature curve prescribed by ASTM E l19 was adopted for the test. This fire insult is used widely throughout the building industry, and therefore much data on building material performance exists. This fire curve is also recognized by the SOLAS Convention and the U.S. Coast Guard (Title 46, Subpart 164.009) and is representative of most Class A fire scenarios. Under consideration by the Navy for "Class B" fires is the UL 1709 and ASTM P 191 fire curves, which reach a higher temperature faster. This would be more representative of a severe hydrocarbon pool-fed fire. Data for one hour of all three of these fire curves are presented in Figure 4-43.

Mechanical Loading

The objective of the thermo-mechanical test program was to evaluate a generic marine structure with realistic live loads during a shipboard fire scenario. A panel structure was chosen, as this could represent decking, bulkheads or hull plating. Loads on marine structures are unique in that there are usually considerable out-of-plane forces that must be evaluated. These forces may be the result of hydrostatic loads or live deck loads from equipment or crew. In-plane failure modes are almost always from compressive forces, rather than tensile.

Given the above discussion, a multi-plane load jig, shown in Figure 4-41, was conceived. This test jig permits simultaneous application of compressive and flexural forces on the test panel during exposure to fire. The normal load is applied with a circular impactor, measuring one square foot. This arrangement is a compromise between a point load and a uniform pressure load. A constant load is maintained on the panel throughout the test, which produces a situation analogous to live loads on a ship during a fire. Failure is determined to be when the panel can no longer resist the load applied to it.

The load applied during the tests was determined by a combination of calculations and trial-and-error with the test jig. Panels 1 through 7 (except 3) were used to experimentally determine appropriate applied pressures in-plane and out-of-plane. The goal of this exercise was to bring the laminate to a point near first ply failure under static conditions. This required loads that were approximately four times a value accepted as a design limit for this type of structure in marine use.

Early screening test showed that the normal deflection of a panel under combined load followed somewhat predictions of a simple two-dimensional beam. For a beam with fixed ends, deflection is:

$$y = \frac{P\,l^3}{192\,E\,I} \qquad (4\text{-}29)$$

For a beam with pinned ends, deflection is:

$$y = \frac{P\, l^3}{48\, E\, I} \qquad (4\text{-}30)$$

where:

y = displacement, inches
P = load, pounds
l = panel span (36 inches)
E = Stiffness, pounds/in^2
I = moment of inertia, in^4

For the test jig with the bottom fixed and the top pinned, the following expression approximates the response of the sandwich panels tested:

$$y = \frac{P\, l^3}{62\, E\, I} \qquad (4\text{-}31)$$

The above expression is used to back out a value for stiffness, *EI*, of the panels during the test that is based on the displacement of the panel at the location that the normal load is applied.

By having one end of the panel pinned in the test fixture, the test laminate effectively models a marine panel structure with a 72" span and fixed ends. If this panel were to be used for the side structure of a deckhouse, the allowable design head under the American Bureau of Shipping Rules for FRP Vessels is about 5 feet.

Finally, the applied compressive load of 6000 pounds works out to be just over 2500 pounds per linear foot. The normal load of 1000 pounds equates to just under 150 pounds per square foot. The full-scale E 119 tests done for the Navy at Southwest Research Institute in September, 1991 [4-40] in support of the Integrated Technology Deckhouse program used compressive loads of 3500 pounds per linear foot and a normal force of 175 pounds per square foot. IMO Resolution MSC.45(65), which establishes test procedures for "fire-resisting" division of high speed craft, calls for 480 pounds per linear foot compressive load on bulkheads and 73 lbs/ft^2 normal load on decks.

Test Panel Selection Criteria

The key parameter that was varied for the test program was panel geometry, rather than resin or insulation. The objective for doing this was to validate the test method for as many different types of composite panel structures.

Most of the test panels were of sandwich construction, as this represents an efficient way to build composite marine vehicles and will be more common than solid laminates for future newbuildings. Each geometry variation was tested in pairs using both a PVC and balsa core material. These materials behave very differently under static, dynamic and high temperature conditions, and therefore deserve parallel study. The following panels were tested:

- Panels 1 and 2 were tested with no load to obtain initial thermocouple data;

- Panel 3 was a bare steel plate that was tested in the middle of the program to serve as a baseline for comparison;
- Panels 4 and 5 were tested with only out-of-plane loads to determine test panel response. Similarly, panels 6 and 7 were used to test in-plane loads only;
- Panels 8 and 9 represented the first test of combined loading at the established test levels;
- Panels 10 and 11 utilized a double core concept to create a "club sandwich" structure. This fire hardened concept, also proposed by Ron Purcell of NSWC, Carderock and Ingalls Shipbuilding, assumes that the inner skin will survive the fire insult to create a sandwich structure with a reduced, but adequate, *I* (the test jig was modified to accommodate panels using this concept that are up to 4" thick and require higher normal loads for testing);
- Panels 12 and 13 used woven reinforcements instead of knits;
- Panel 14 had a staggered stiffener geometry, which has been shown to reduce the transmission of mechanical vibrations. This concept was tested to determine if the heat transfer path would also be retarded. This panel was also the only one tested with an air gap as an insulator;
- Panel 15 was made with a very dry last layer of E-glass and a single layer of insulation;
- Panels 16 and 17 were made from 1/2" cores with hat-stiffeners applied. These tests were performed to determine if secondary bonds would be particularly susceptible to elevated temperature exposure;
- Panels 18 and 19 had carbon fiber reinforcement in their skins;
- Panels 20 and 21 were made with flame retardant modifiers in the resin system, 5% Nyacol and 25% ATH, respectively. These tests were performed to determine the effect these additives had on elevated temperature mechanical performance.;
- Panel 22 used a higher density PVC core;
- Panel 23 used the "ball" shaped loading device;
- Panel 24 was a PVC-cored sandwich panel with aluminum skins, with insulation. Panel 25 was the same as 24, without any insulation;
- Panels 26 and 27 were solid laminates, using vinyl ester and iso polyester resins, respectively;
- Panels 28 and 29 were tested with the "line" loading device; and
- Panel 30 was a balsa-cored sandwich panel with aluminum skins.

Test Results

The general arrangement for panels tested with insulation is shown in Figure 4-48. The thermo-mechanical test data for panels evaluated under this program was presented in plots similar to Figure 4-49.

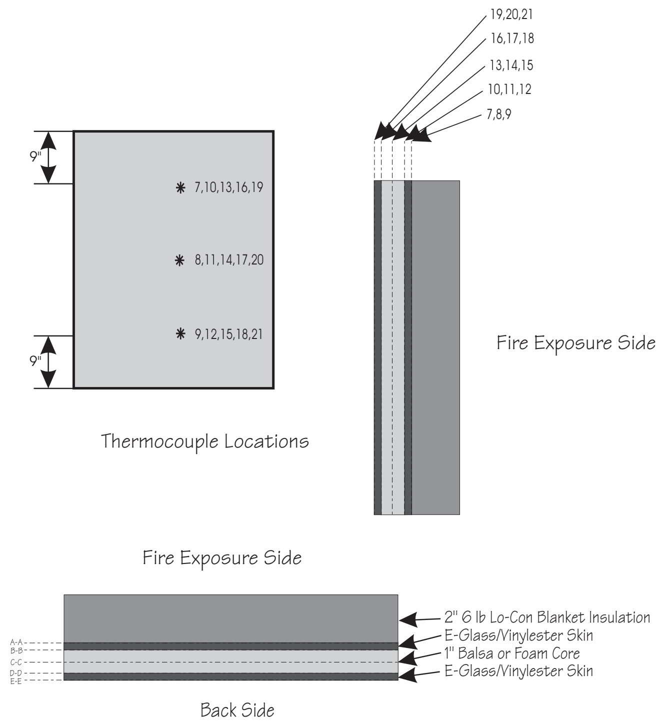


Figure 4-48 General Arrangement for 3-foot Panels Tested under E-119 Insult with Insulation

Balsa versus PVC Core

As a general rule, the sandwich laminates with balsa cores would endure the full 60 minutes of the E 119 test. Stiffness reduction was only to about 50% of the original stiffness. As the panels were loaded to first ply failure before the furnace was started, a residual safety factor of about two was realized with these structures. By contrast, the PVC cores behaved as a thermoplastic material is expected to and gradually lost stiffness after a period of time. This usually occurred after about 40 minutes. Stiffness reduction was normally to 25%, which still left a safety factor of one just before failure.

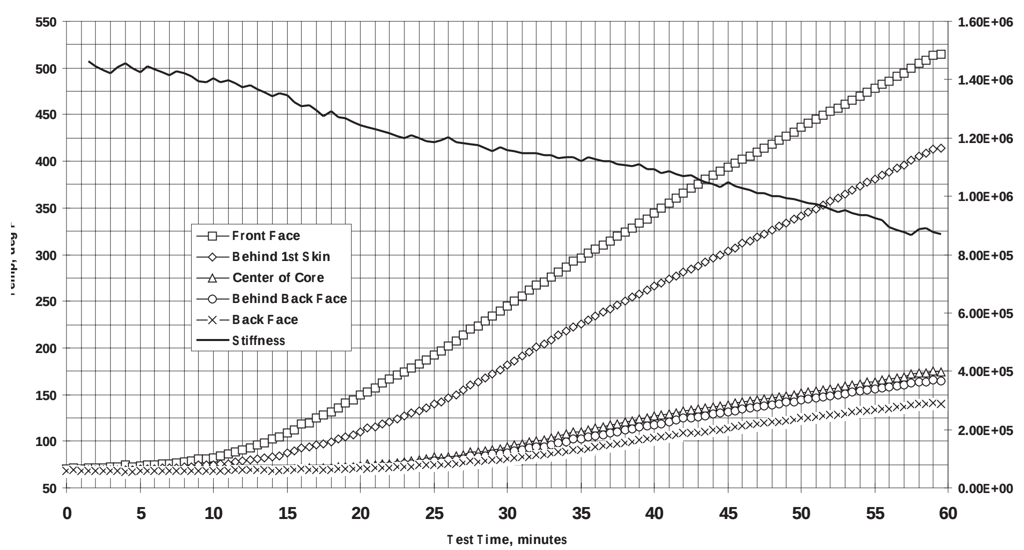


Figure 4-49 Stiffness and Temperature Data for Balsa-Cored E-Glass/Vinyl Ester Panel with 2″ Lo-Con Ceramic Insulation Tested with Multiplane Load Jig and E-119 Fire

The consistency shown in test duration and stiffness reduction characteristics for a variety of geometries suggests that the test procedure is a valid method for evaluating how composite material structures would behave during a fire. Although the PVC-cored laminates failed through stiffness reduction sooner than balsa cores, the panels usually did not show signs of skin to core debonding because to cores got soft and compliant. If loads were removed from the PVC panels after the test, the panel would return to its near normal shape. Conversely, if load was maintained after the test, permanent deformation would remain. Data for a balsa-cored panel, which was one of the better performers, is presented in Figure 4-49.

Steel Plate, Unprotected

Steel plates of 1/4" nominal thickness were tested in the load jig without insulation to characterize how this typical shipboard structure would behave during a fire. The initial plate was loaded to 2000 pounds in-plane, which turned out to cause Euler buckling as the stiffness of the steel reduced. The test was repeated with minimal loads of 500 pounds, but the plate still failed after about 18 minutes. It should be noted that the back face temperature exceeded 1000 °F.

Double 1/2" Cores - “Club Sandwich”

Both the PVC and the balsa double core configurations endured the full 60 minute test. The PVC-cored panel saw a stiffness reduction to about 25%, while the balsa only went to 50%. Both panels lost stiffness in a near linear fashion, which suggests that this is a suitable fire-hardening concept.

Woven Roving Reinforcement

The panels made with woven roving E-Glass reinforcement behaved similarly to those made with knit reinforcements. On a per weight basis, the knit reinforcements generally have better mechanical properties.

Staggered Stiffener

The staggered stiffener panel proved to perform very well during the fire tests, albeit at a significant weight penalty. It is interesting to note that temperatures behind the insulation never exceeded 350°F, a full 200° cooler than the other panels. The air gap insulation technique deserves further study.

Dry E-Glass Finish

Thermocouple data has shown that the thermoconductivity of and FRP ply reduces an order of magnitude as the resin becomes pyrolyzed. Going on this theory, a panel was constructed with a heavy last E-Glass ply that was not thoroughly wetted out. This produced a panel with a dry fiberglass finish. Although this did not perform as well, as 1" of ceramic blanket, it did insulate the equivalent of 0.25". This finish also provides a surface that could provide a good mechanical bond for application of a fire protection treatment, such as a phenolic skin or intumescent paint.

Stiffened Panels

The hat-stiffened panels performed somewhat better than expected, with no delamination visible along the stringer secondary bond. Although temperatures at the top of the hat section got to 650°F, the side wall remained intact, thus providing sufficient stiffness to endure 50 - 55 minutes of testing. The performance difference between the balsa and PVC panels was not so apparent with this configuration.

Carbon Fiber Reinforcement

The addition of carbon fiber reinforcement to the skins did not significantly change the fire performance of the laminate. Overall, the stiffness of the panels increased greatly with the modest addition of carbon fiber. The modulus of the skins was best matched to the structural performance of the balsa core.

Flame Retardants

Flame retardants are generally added to resin systems to delay ignition and/or reduce flame spread rate. Both the formulations tested did not significantly degrade the elevated temperature mechanical performance of the laminates. The ATH performed slightly better than the Nyacol.

High Density PVC Core

Because a consistent thermal degradation of the PVC cores was noted after about 40 minutes, a high density H-130 was tested. This panel unfortunately failed after about the same amount of time due to a skin-to-core debond. This failure mode is often common when the mechanical properties of the core material are high.

Load with Ball Impactor

A spherical ball loading device was used on a PVC-cored panel to see if the test results would be altered with this type of load. The results were essentially the same as with the flat load application device.

Aluminum Skins

PVC-cored panels with aluminum failed slightly sooner than their composite counterparts. The insulated, balsa-cored panel with aluminum skins endured the entire test, with only modest stiffness reduction. The temperature behind the insulation never got above 450°F, which suggests that significant lateral heat transfer along the aluminum face may have been occurring.

Solid Laminates

The solid laminates were able to maintain relatively low front face temperatures due to overall improved through-thickness thermal conduction, as compared to sandwich laminates. The vinyl ester laminate performed better than the ortho polyester.

Line Load Device

A line loading device was used on PVC-cored and balsa-cored panels to see if the test results would be altered with this type of load. The results were essentially the same as with the flat load application device.

Manufacturing Processes

The various fabrication processes applicable to marine composite structures are summarized in the tables at the end of this section. The most common technique used for large structures such as boat hulls, is the open mold process. Specifically, hand lay-up or spray-up techniques are used. Spray-up of chopped fibers is generally limited to smaller hulls and parts. Figure 5-1 shows the results of an industry survey indicating the relative occurrence of various manufacturing processes within the marine industry. The most popular forms of open molding in the marine industry are single-skin from female molds, cored construction from female molds and cored construction from male mold. Industry survey results showing the popularity of these techniques is shown in Figure 5-2.

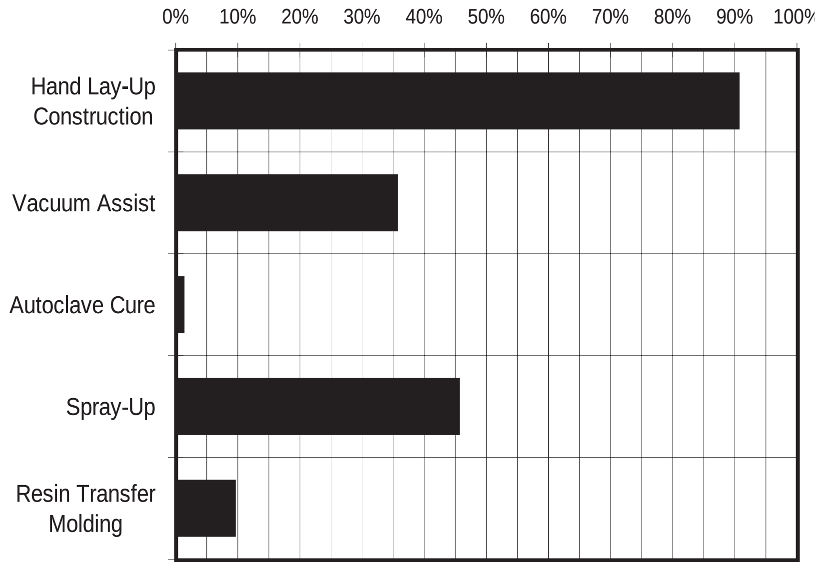


Figure 5-1 Building Processes [EGA Survey]

Mold Building

Almost all production hull fabrication is done with female molds that enable the builder to produce a number of identical parts with a quality exterior finish. It is essential that molds are carefully constructed using the proper materials if consistent finish quality and dimensional control are desired.

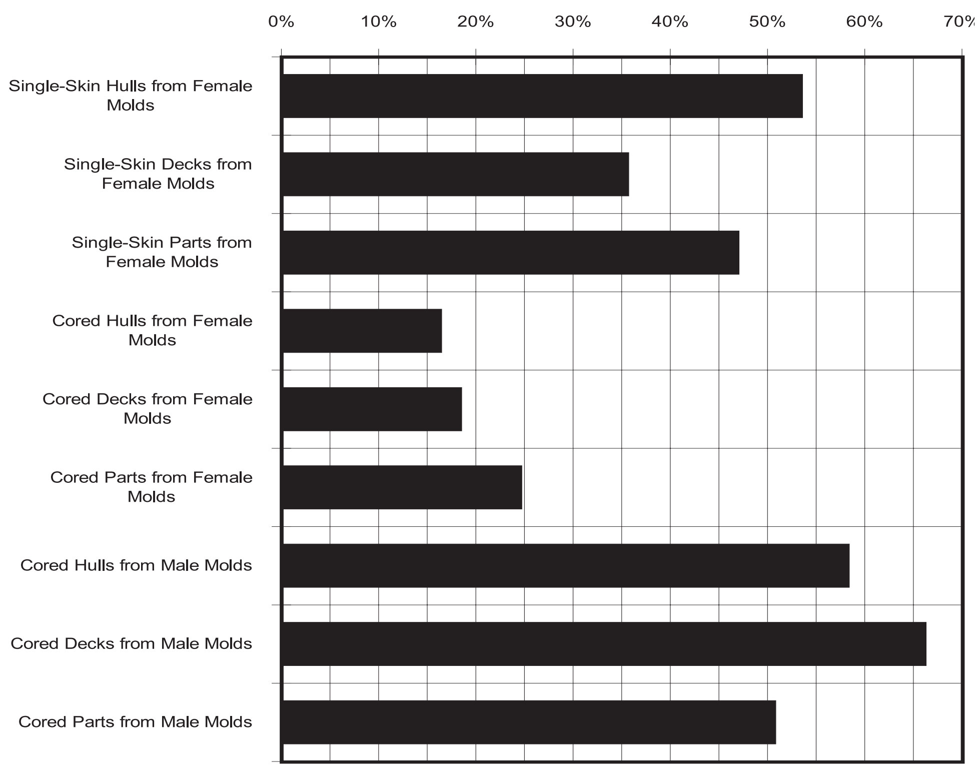


Figure 5-2 Marine Industry Construction Methods [EGA Survey]

Plugs

A mold is built over a plug that geometrically resembles the finished part. The plug is typically built of non-porous wood, such as oak, mahogany or ash. The wood is then covered with about three layers of 7.5 to 10 ounce cloth or equivalent thickness of mat. The surface is faired and finished with a surface curing resin, with pigment in the first coat to assist in obtaining a uniform surface. After the plug is wet-sanded, three coats of carnauba wax and a layer of PVA parting film can be applied by hand.

Molds

The first step of building a mold on a male plug consists of gel coat application, which is a critical step in the process. A non-pigmented gel coat that is specifically formulated for mold applications should be applied in 10 mil layers to a thickness of 30 to 40 mils. The characteristics of tooling gel coats include: toughness, high heat distortion, high gloss and good glass retention. A back-up layer of gel that is pigmented to a dark color is then applied to enable the laminator to detect air in the production laminates and evenly apply the production gel coat surfaces.

After the gel coat layers have cured overnight, the back-up laminate can be applied, starting with a surfacing mat or veil to prevent print-through. Reinforcement layers can consist of either mat and cloth or mat and woven roving to a minimum thickness of $\frac{1}{4}$ inch. Additional thickness or coring can be used to stiffen large molds. Framing and other stiffeners are required to strengthen the overall mold and permit handling. The mold should be post cured in a hot-air oven at 100°F for 12 to 24 hours. After this, wet-sanding and buffing can be undertaken. The three layers of wax and PVA are applied in a manner similar to the plug. [5-1]

Figure 5-3 One-Off Female Mold Built by Light Industries [author photo]

Figure 5-4 Production Female Mold on Spindle at Corsair Marine [author photo]

Figure 5-5 Metal Stiffened Female Mold at Northcoast Yachts [author photo]

Figure 5-6 Batten Construction of Female Mold at Westport Shipyard [Westport photo]

Figure 5-7 Expandable Female Mold at Northcoast Yachts [author photo]

Figure 5-8 Large Female Mold Stored Outdoors at Trident Shipyard [author photo]

Figure 5-9 Detail Construction of a Deckhouse Plug at Heisley Marine [author photo]

Single Skin Construction

Almost all marine construction done from female molds is finished with a gel coat surface. Therefore, this is the first procedure in the fabrication sequence. Molds must first be carefully waxed and coated with a parting agent. Gel coat is sprayed to a thickness of 20 to 30 mils and allowed to cure. A back-up reinforcement, such as a surfacing mat, veil or polyester fabric is then applied to reduce print-through. Recent testing has shown that the polyester fabrics have superior mechanical properties while possessing thermal expansion coefficients similar to common resin systems. [5-2]

Resin can be delivered either by spray equipment or in small batches via buckets. If individual buckets are used, much care must be exercised to ensure that the resin is properly catalyzed. Since the catalyzation process is very sensitive to temperature, ambient conditions should be maintained between 60° and 85°F. Exact formulation of catalysts and accelerators is required to match the environmental conditions at hand.

Reinforcement material is usually pre-cut outside the mold on a flat table. Some material supply houses are now offering pre-cut kits of reinforcements to their customers. [5-3] After a thin layer of resin is applied to the mold, the reinforcement is put in place and resin is drawn up by rolling the surface with mohair or grooved metal rollers, or with squeegees. This operation is very critical in hand lay-up fabrication to ensure complete wet-out, consistent fiber/resin ratio, and to eliminate entrapped air bubbles.

After the hull laminating process is complete, the installation of stringers and frames can start. The hull must be supported during the installation of the interior structure because the laminate will not have sufficient stiffness to be self-supporting. Secondary bonding should follow the procedures outlined in the Design Section starting on page 166.

Cored Construction from Female Molds

Cored construction from female molds follows much the same procedure as that for single skin construction. The most critical phase of this operation, however, is the application of the core to the outer laminate. The difficulty stems from the following:

- Dissimilar materials are being bonded together;
- Core materials usually have some memory and resist insertion into concave molds;
- Bonding is a "blind" process once the core is in place;
- Contoured core material can produce voids as the material is bent into place; and
- Moisture contamination of surfaces.

Investigators have shown that mechanical properties can be severely degraded if voids are present within the sandwich structure. [5-4] Most suppliers of contoured core material also supply a viscous bedding compound that is specially formulated to bond these cores. Where part geometry is nearly flat, non-contoured core material is preferable. In the case of PVC foams, preheating may be possible to allow the material to more easily conform to a surface with compound curves. Vacuum bag assistance is recommended to draw these cores down to the outer laminate and to pull resin up into the surface of the core.

Cored Construction over Male Plugs

When hulls are fabricated on a custom basis, boat builders usually do not go through the expense of building a female mold. Instead, a male plug is constructed, over which the core material is placed directly. Builders claim that a better laminate can be produced over a convex rather than a concave surface.

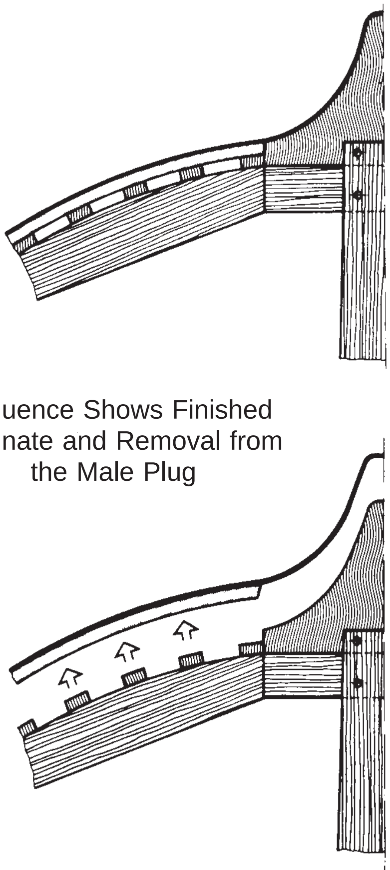
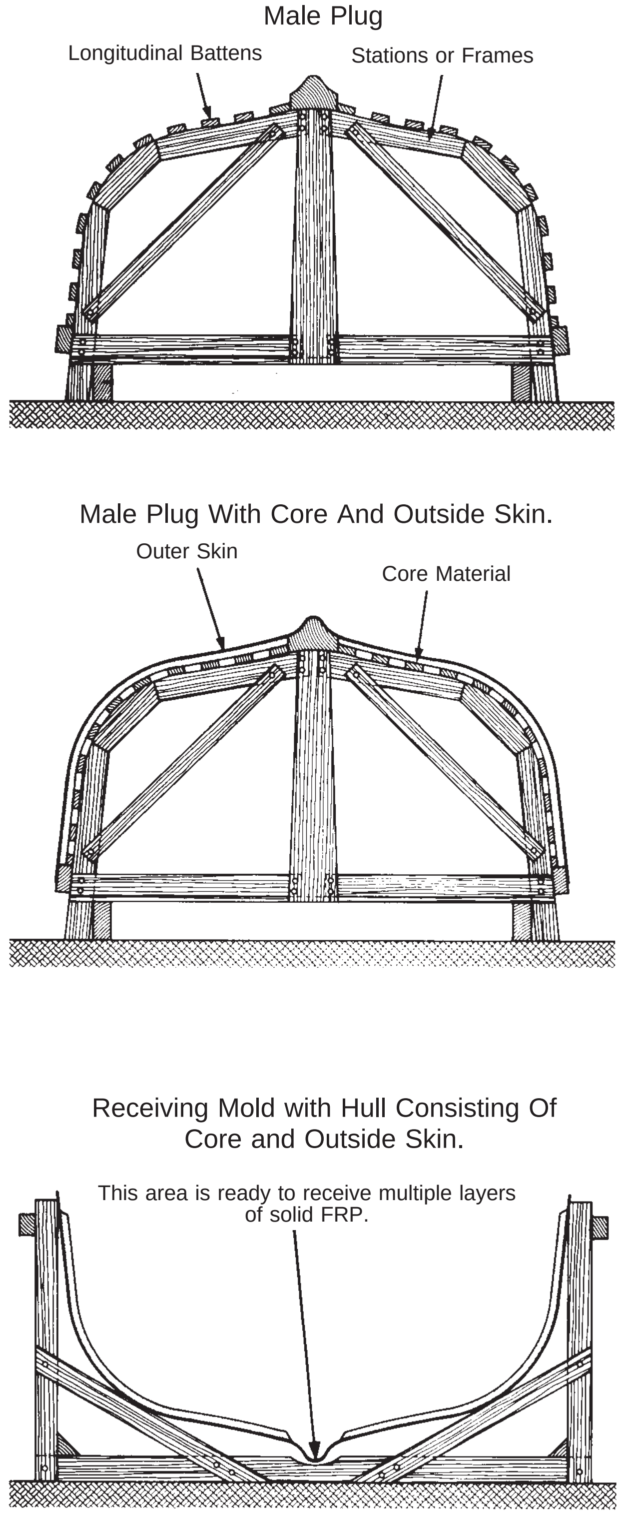


Figure 5-10 Detail of Sandwich Construction over Male Plug [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]



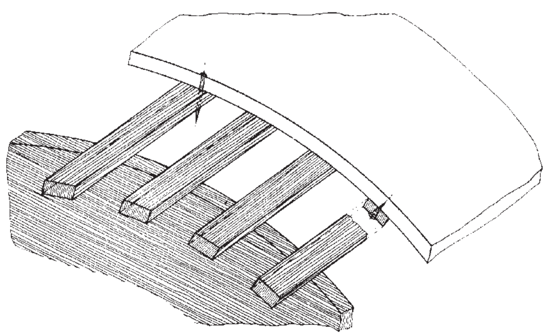


Figure 5-11 Detail of Foam Placement on Plugs Showing Both Nails from the Outside and Screws from the Inside [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]

Figure 5-12 Simple, Wood Frame Male Plug used in Sandwich Construction [Johannsen, *One-Off Airex Fiberglass Sandwich Construction*]

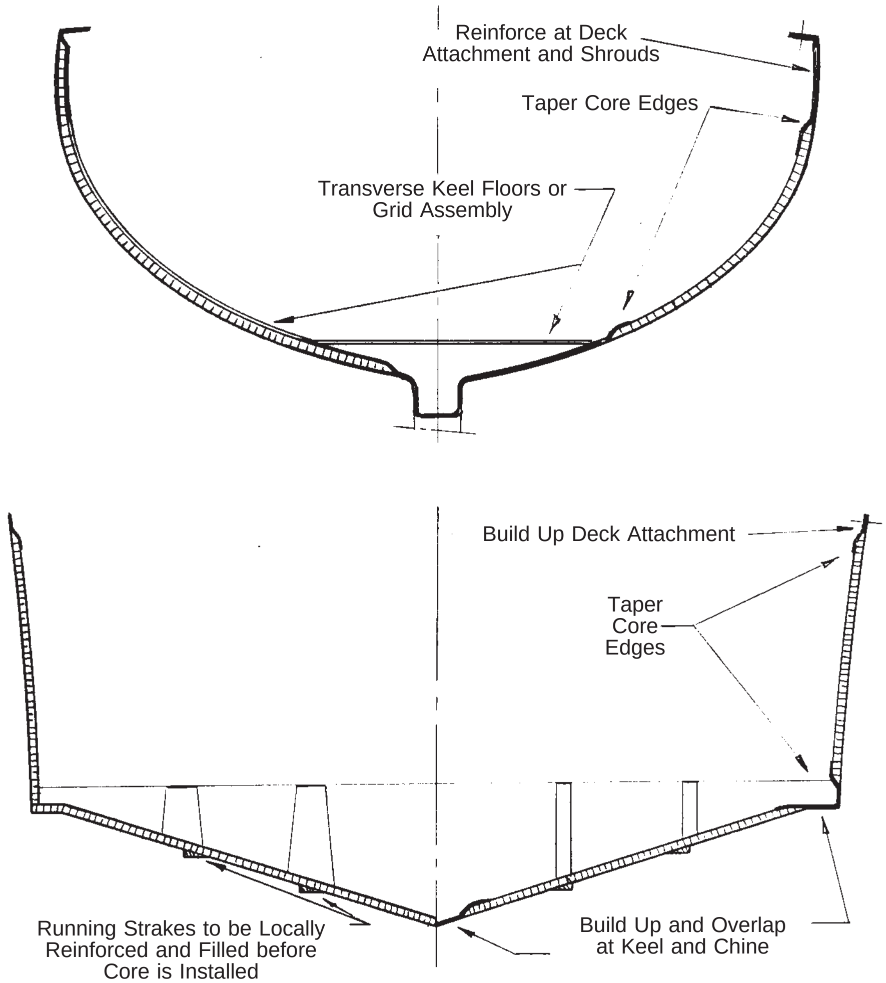


Figure 5-13 Typical Sail and Power Cored Construction Midship Section [Walton, Baltek]

Figure 5-12 shows the various stages of one-off construction from a male plug. (A variation of the technique shown involves the fabrication of a plug finished to the same degree as described above under Mold Making. Here, the inner skin is laminated first while the hull is upside-down. This technique is more common with balsa core materials.) A detail of the core and outer skin on and off of the mold is shown in Figure 5-10.

With linear PVC foam, the core is attached to the battens of the plug with either nails from the outside or screws from the inside, as illustrated in Figure 5-11. If nails are used, they are pulled through the foam after the outside laminate has cured. Screws can be reversed out from inside the mold.

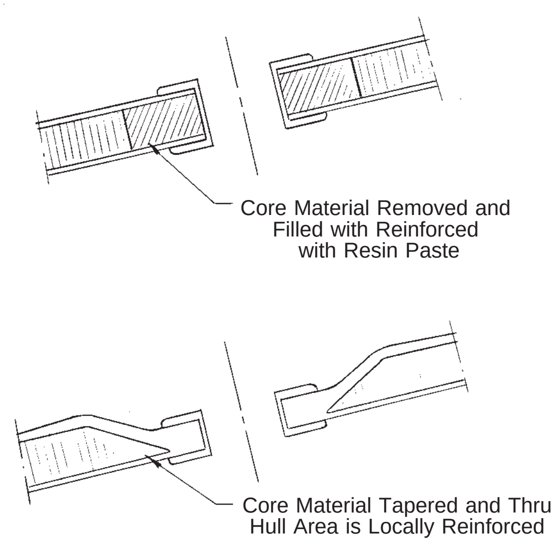


Figure 5-14 Recommended Thru-Hull Connection for Cored Hulls [Walton, Baltek]

Figure 5-15 Material Layout Table at Heisley Marine [author photo]

Figure 5-16 Hull and Scaffolding Set Up at Northcoast Yachts [author photo]

Figure 5-17 Resin is Applied to a Plywood Form at Heisley Marine [author photo]

Figure 5-18 Workers Laminate Hull at Northcoast Yachts [author photo]

Figure 5-19 Detail Glued Prior to Lamination at Corsair Marine [author photo]

Productivity

It is always difficult to generalize about productivity rates within the marine composites industry. Data is very dependent upon how "custom" each unit is, along with geometric complexity and material sophistication. Techniques also vary from builder to builder, which tend to enforce theories about economies of scale. High volume operations can support sophisticated molds and jigs, which tends to reduce unit cost. Table 5-1 is a source of rough estimating data as it applies to various types of construction.

Table 5-1 Marine Composite Construction Productivity Rates [Bob Scott & BLA]

Source	Type of Construction	Application	Lbs/Hour*	Ft^2/Hour†	Hours/Ft^2‡
Scott *Fiberglass Boat Construction*	Single Skin with Frames	Recreational	20*	33†	.03‡
		Military	12*	20†	.05‡
	Sandwich Construction	Recreational	10*	17†	.06‡
		Military	6*	10†	.10‡
BLA *Combatant Feasibility Study*	Single Skin with Frames	Flat panel (Hull)	13**	22**	.05**
		Stiffeners & Frames	5**	9**	.12**
	Core Preparation for Sandwich Construction	Flat panel (Hull)	26**	43**	.02**
		Stiffeners	26**	43**	.02**
	Vacuum Assisted Resin Transfer Molding (VARTM)	Flat panel (Hull)	10§	43§	.02§
		Stiffeners	7§	14§	.07§

* Based on mat/woven roving laminate
** Based on one WR or UD layer
† Single ply of mat/woven roving laminate
‡ Time to laminate one ply of mat/woven roving
§ Finished single ply based on weight of moderately thick single-skin laminate

Figure 5-20 Hardware Placement Jig is Lowered Over Recently Laminated Deck at Corsair Marine [author photo]

Figure 5-21 Complex Part is Prepped for Secondary Bond at Westport Shipyard [author photo]

Equipment

Various manufacturing equipment is used to assist in the laminating process. Most devices are aimed at either reducing man-hour requirements or improving manufacturing consistency. Figure 5-22 gives a representation of the percentage of marine fabricators that use the equipment described below.

Chopper Gun and Spray-Up

A special gun is used to deposit a mixture of resin and chopped strands of fiberglass filament onto the mold surface that resembles chopped strand mat. The gun is called a "chopper gun" because it draws continuous strands of fiberglass from a spool through a series of whirling blades that chop it into strands about two inches long. The chopped strands are blown into the path of two streams of atomized liquid resin, one accelerated and one catalyzed (known as the two-pot gun). When the mixture reaches the mold, a random pattern is produced.

Alternately, catalyst can be injected into a stream of promoted resin with a catalyst injector gun. Both liquids are delivered to a single-head, dual nozzle gun in proper proportions and are mixed either internally or externally. Control of gel times with this type of gun is accomplished by adjusting the rate of catalyst flow. Spray systems may also be either airless or air-atomized. The airless systems use hydraulic pressure to disperse the resin mix. The air atomized type introduces air into the resin mix to assist in the dispersion process. Figures 5-23 and 5-24 illustrate the operation of air-atomizing and airless systems.

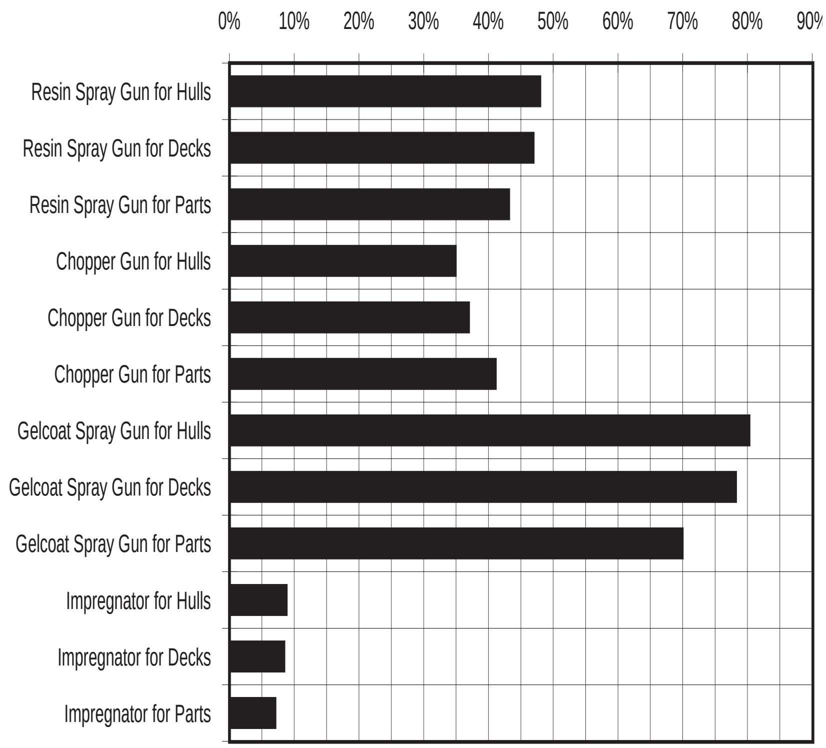


Figure 5-22 Manufacturing Equipment [EGA Survey]

Resin and Gel Coat Spray Guns

High-volume production shops usually apply resin to laminates via resin spray guns. A two-part system is often used that mixes separate supplies of catalyzed and accelerated resins with a gun similar to a paint sprayer. Since neither type of resin can cure by itself without being added to the other, this system minimizes the chances of premature cure of the resin. This system provides uniformity of cure as well as good control of the quantity and dispersion of resin. Resin spray guns can also be of the catalyst injection type described above. Table 5-2 provides a summary of the various types of spray equipment available. Air atomized guns can either be the internal type illustrated in Figure 5-25 or the external type shown in Figure 5-26.

Table 5-2 Description of Spray Equipment
[Cook, *Polycor Polyester Gel Coats and Resins*]

Process	Technique	Description
Material Delivery	Gravity	The material is above the gun and flows to the gun (not commonly used for gel coats - sometimes used for more viscous materials).
	Suction	The material is picked up by passing air over a tube inserted into the material (no direct pressure on the material). Not commonly used for making production parts due to slow delivery rates.
	Pressure	The material is forced to the gun by direct air pressure or by a pump. Pressure feed systems - mainly pumps - are the main systems used with gel coats.
Method of Catalyzation	Hot Pot	Catalyst is measured into a container (pressure pot) and mixed by hand. This is the most accurate method but requires the most clean up.
	Catalyst Injection	Catalyst is added and mixed at or in the gun head requiring Cypriot lines and a method of metering catalyst and material flow. This is the most common system used in larger shops.
Atomization	Internal	Air and resin meet inside the gun head and come out a single orifice. This system is not recommended for gel coats as it has a tendency to cause porosity and produce a rougher film. Internal mix air nozzles are typically used in high production applications where finish quality is not critical. The nozzles are subject to wear, although replacement is relatively inexpensive. Some materials tend to clog nozzles.
	External	Air and resin meet outside the gun head or nozzle. This is the most common type of spray gun. The resin is atomized in three stages: First Stage Atomization - fluid leaving the nozzle orifice is immediately surrounded by an envelope of pressurized air emitted from an annular ring. Second Stage Atomization - the fluid stream next intersects two streams of air from converging holes indexed to 90° to keep the stream from spreading. Third Stage Atomization - the "wings" of the gun have air orifices that inject a final stream of air designed to produce a fan pattern.
	Airless Atomization	Resin is pressurized to 1200 to 2000 psi via a high ratio pump. The stream atomizes as it passes through the sprayer orifice. This system is used for large and high volume operations, as it is cleaner and more efficient than air atomized systems.
	Air Assist Airless	Material is pressurized to 500 to 1000 psi and further atomized with low pressure air at the gun orifice to refine the spray pattern.

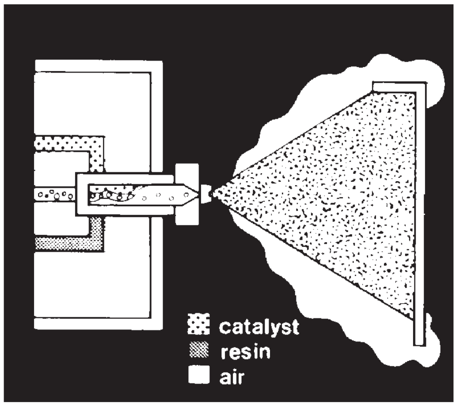


Figure 5-23 Air Atomizing Gun Showing Possible "Fog" Effect at Edge of Spray Pattern [Venus-Gusmer]

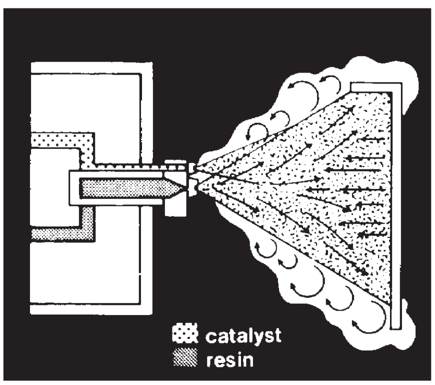


Figure 5-24 Airless Spray Gun Showing Possible Bounce Back from the Mold [Venus-Gusmer]

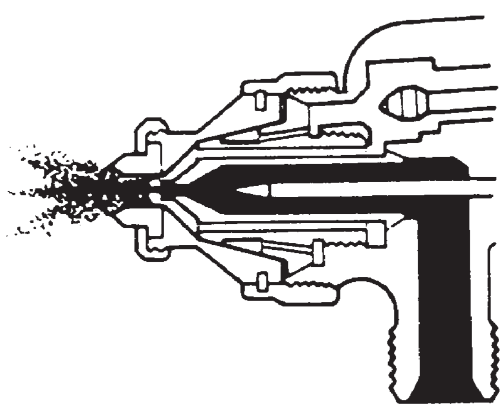


Figure 5-25 Internal Atomization Spray Gun [Binks Mfg.]

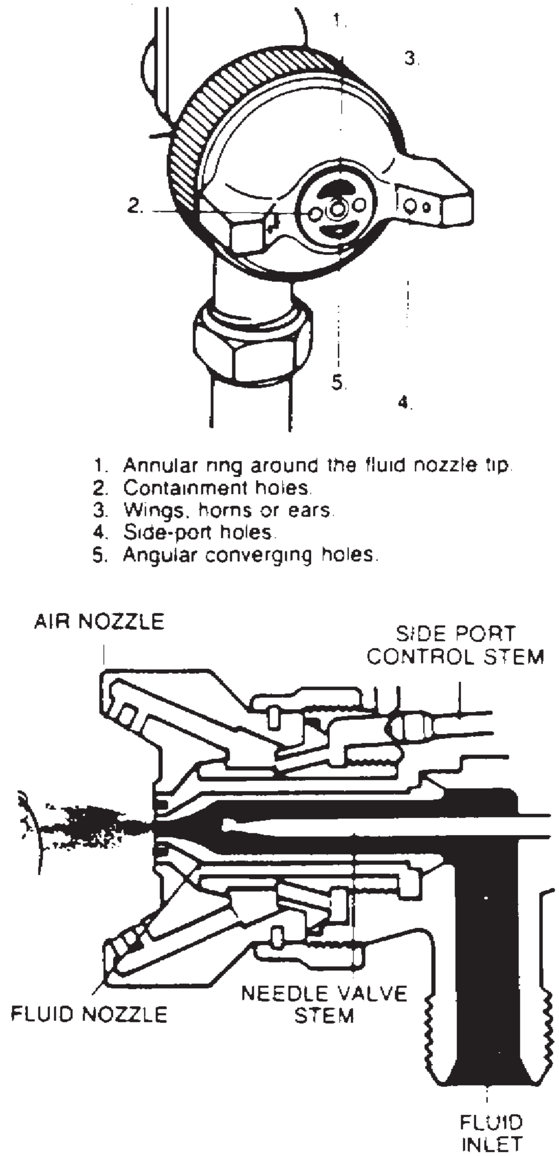


Figure 5-26 External Atomization Spray Gun [Binks Mfg.]

Impregnator

Impregnators are high output machines designed for wetting and placing E-glass woven roving and other materials that can retain their integrity when wetted. These machines can also process reinforcements that combine mat and woven roving as well as Kevlar®.

Laminates are laid into the mold under the impregnator by using pneumatic drive systems to move the machine with overhead bridge-crane or gantries. Figures 5-28 and 5-29 show a configuration for a semi-gantry impregnator, which is used when the span between overhead structural members may be too great.

Roll goods to 60 inches can be wetted and layed-up in one continuous movement of the machine. The process involves two nip rollers that control a pool of catalyzed material on either side of the reinforcement. An additional set of rubber rollers is used to feed the reinforcement through the nip rollers and prevent the reinforcement from being pulled through by its own weight as it drops to the mold. Figure 5-27 is a schematic representation of the impregnator material path.

Impregnators are used for large scale operations, such as mine countermeasure vessels, 100 foot yachts and large volume production of barge covers. In addition to the benefits achieved

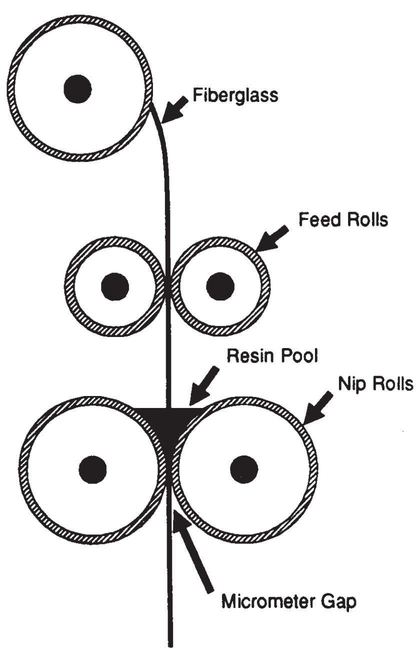


Figure 5-27 Impregnator Material Path [Raymer, *Large Scale Processing Machinery for Fabrication of Composite Hulls and Superstructures*]

Figure 5-28 Impregnator at Westport Shipyard [author photo]

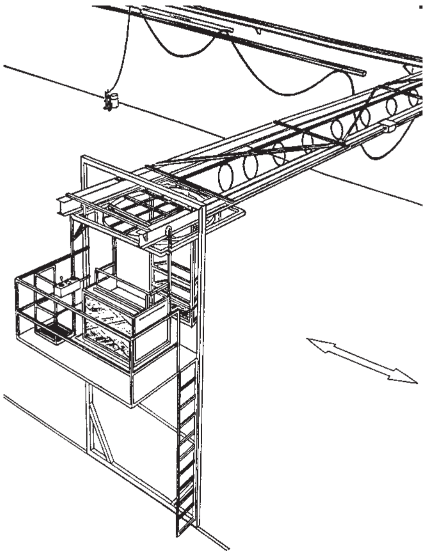


Figure 5-29 Configuration of Semi-Gantry Impregnator [Venus-Gusmer]

Figure 5-30 Laminators Consolidate Reinforcement Material Applied by Impregnator at Westport Shipyard [author photo]

through reduction of labor, quality control is improved by reducing the variation of laminate resin content. High fiber volumes and low void content are also claimed by equipment manufacturers. [5-5]

Health Considerations

This document's treatment of the industrial hygiene topic should serve only as an overview. Builders are advised to familiarize themselves with all relevant federal, state and local regulations. An effective in-plant program considers the following items: [5-6]

- Exposure to styrene, solvents, catalysts, fiberglass dust, noise and heat;
- The use of personal protective equipment to minimize skin, eye and respiratory contact to chemicals and dust;
- The use of engineering controls such as ventilation, enclosures or process isolation;
- The use of administrative controls, such as worker rotation, to minimize exposure;
- Work practice control, including material handling and dispensing methods, and storage of chemicals; and
- A hazard communication program to convey chemical information and safe handling techniques to employees.

Some health related terminology should be explained to better understand the mechanisms of worker exposure and government regulations. The relationship between the term “toxicity” and “hazard” should first be defined. All chemicals are toxic if they are handled in an unsafe manner. Alternatively, “hazard” takes into account the toxicity of an agent and the exposure that a worker has to that agent. “Acute toxicity” of a product is its harmful effect after short-term exposure. “Chronic toxicity” is characterized by the adverse health effects which have been caused by exposure to a substance over a significant period of time or by long-term effects resulting from a single or few doses. [5-7]

Exposure to agents can occur several ways. Skin and eye contact can happen when handling composite materials. At risk are unprotected areas, such as hands, lower arms and face. “Irritation” is defined as a localized reaction characterized by the presence of redness and swelling, which may or may not result in cell death. “Corrosive” materials will cause tissue destruction without normal healing. During the manufacturing and curing of composites, the release of solvents and other volatiles from the resin system can be inhaled by workers. Fiber and resin grinding dust are also a way that foreign agents can be inhaled. Although not widely recognized, ingestion can also occur in the work place. Simple precautions, such as washing of hands prior to eating or smoking can reduce this risk.

Worker exposure to contaminants can be monitored by either placing a sophisticated pump and air collection device on the worker or using a passive collector that is placed on the worker's collar. Both techniques require that the interpretation of data be done by trained personnel. Exposure limits are based on standards developed by the American Conference of Governmental Industrial Hygienists (ACGIH) as follows:

> **Threshold Limit Value - Time Weighted Average (TLV-TWA)** - the time-weighted average for a normal 8-hour workday and a 40-hour workweek, to which nearly all workers may be exposed, day after day, without adverse effect.
>
> **Threshold Limit Value - Short Term Exposure Limit (TLV-STEL)** - the concentration to which workers can be exposed continuously for a short period of time (15 minutes) without suffering from (1) irritation, (2) chronic or irreversible tissue damage, or (3) narcosis of sufficient degree to increase the likelihood of accidental injury, impair self-rescue or materially reduce work efficiency (provided that the daily TLV-TWA is not exceeded).
>
> **Threshold Limit Value - Ceiling (TLV-C)** - the concentration that should not be exceeded during any part of the working day.

The Occupational Safety and Health Administration (OSHA) issues legally binding Permissible Exposure Limits (PELs) for various compounds based on the above defined exposure limits. The limits are published in the Code of Federal Regulations 29 CFR 19100.1000 and are contained in OSHA's revised Air Contaminant Standard (OSHA, 1989). Table 5-3 lists the permissible limits for some agents found in a composites fabrication shop.

Table 5-3 Permissible Exposure Limits and Health Hazards of Some Composite Materials [SACMA, *Safe Handling of Advanced Composite Material Components: Health Information*]

Component	Primary Health Hazard	TLV-TWA	TLV-STEL
Styrene Monomer	Styrene vapors can cause eye and skin irritation. It can also cause systemic effects on the central nervous system.	50 ppm	100 ppm
Acetone	Overexposure to acetone by inhalation may cause irritation of mucous membranes, headache and nausea.	750 ppm	1000 ppm
Methyl ethyl keytone (MEK)	Eye, nose and throat irritation.	200 ppm	300 ppm
Polyurethane Resin	The isicyanates may strongly irritate the skin and the mucous membranes of the eyes and respiratory tract.	0.005 ppm	0.02 ppm
Carbon and Graphite Fibers	Handling of carbon and graphite fibers can cause mechanical abrasion and irritation.	10 mg/m^{3*}	—
Fiberglass	Mechanical irritation of the eyes, nose and throat.	10 $mg/m^{3\dagger}$	—
Aramid Fibers	Minimal potential for irritation to skin.	5 $fibrils/cm^{3\ddagger}$	—
* Value for total dust - natural graphite is to be controlled to 2.5 mg/m^3			
† Value for fibrous glass dust - Although no standards exist for fibrous glass, a TWA of 15 mg/m^3 (total dust) and 5 mg/m^3 (respirable fraction) has been established for "particles not otherwise regulated"			
‡ Acceptable exposure limit established by DuPont based on internal studies			

The boat building industry has expressed concern that the PELs for styrene would be extremely costly to achieve when large parts, such as hulls, are evaluated. In a letter to the Fiberglass Fabrication Association (CFA), OSHA stated:

> "The industry does not have the burden of proving the technical infeasibility of engineering controls in an enforcement case....The burden of proof would be on OSHA to prove that the level could be attained with engineering and work practice controls in an enforcement action if OSHA believed that was the case." [5-8]

OSHA also stated that operations comparable to boat building may comply with the PELs through the use of respiratory protection when they:

> "(1) employ the manual or spray-up process, (2) the manufactured items utilize the same equipment and technology as that found in boat building, and (3) the same consideration of large part size, configuration interfering with airflow control techniques, and resin usage apply."

The use of proper ventilation is the primary technique for reducing airborne contaminants. There are three types of ventilation used in FRP fabrication shops:

General (Dilution) Ventilation. The principal of dilution ventilation is to dilute contaminated air with a volume of fresh air. Figure 5-31 shows good and bad examples of general ventilation systems. These types of systems can be costly as the total volume of room air should be changed approximately every 2 to 12 minutes.

Local Ventilation. A local exhaust system may consist of a capture hood or exhaust bank designed to evacuate air from a specific area. Spray booths are an example of local ventilation devices used in shops where small parts are fabricated.

Directed-Flow Ventilation. These systems direct air flow patterns over a part in relatively small volumes. The air flow is then captured by an exhaust bank located near the floor, which establishes a general top-to-bottom flow. [5-6]

One yard in Denmark, Danyard Aalborg A/S, has invested a significant amount of capital to reach that country's standards for styrene emission during the fabrication of fiberglass multipurpose naval vessels. Total allowable PELs in Denmark are 25 ppm, which translates to about 12 ppm for styrene when other contaminants are considered. The air-handling system that they've installed for a 50,000 square foot shop moves over 5 million cubic feet per hour, with roughly two thirds dedicated to styrene removal and one third for heating. [5-9]

Many U.S. manufacturers are switching to replacement products for acetone to clean equipment as an effort to reduce volatiles in the work place. Low-styrene emission laminating resins have been touted by their manufacturers as a solution to the styrene exposure problem. An example of such a product is produced by US Chemicals and is claimed to have a 20% reduction in styrene monomer content. [5-10] To document company claims, worker exposure in Florida and California boat building plants were monitored for an 8-hour shift. In the Florida plant, average worker exposure was 120 ppm for the conventional resin and 54 ppm for the low-styrene emission resin. The California plant showed a reduction of 31% between resin systems. Table 5-4 is a breakdown of exposure levels by job description.

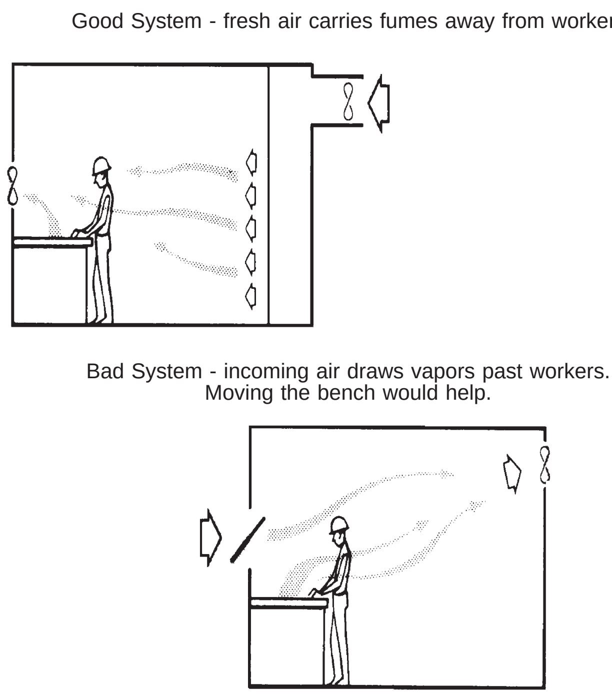


Figure 5-31 General Ventilation Techniques to Dilute Airborne Contaminants through Air Turnover [FRP Supply, *Health, Safety and Environmental Manual*]

Table 5-4 Personnel Exposure to Styrene in Boat Manufacturing [Modern Plastics, *Low-Styrene Emission Laminating Resins Prove it in the Work place*]

Worker Occupation	Styrene Exposure, TLV-TWA	
	Standard Resin	Low-Styrene Emission Resin
Florida Plant		
Hull gun runner	113.2	64.0
Gun runner 1	158.2	37.7
Gun runner 2	108.0	69.6
Gun runner 3	80.3	43.9
Roller 1	140.1	38.4
Roller 2	85.1	43.6
Roller 3	131.2	56.9
California Plant		
Foreman (chopper)	30	7
Chopper 2	106	77
Chopper 3	41	47
Roller 1	75	37
Roller 2	61	40
Roller 3	56	42
Area sampler 1	18	12
Area sampler 2	19	4
Area sampler 3	9	13
Area sampler 4	30	16

Vacuum Bagging

An increasing number of builders are using vacuum bag techniques to produce custom and production parts. By applying a vacuum over a laminate, consolidation of reinforcement materials can be accomplished on a consistent basis. A vacuum pressure of 14.7 psi is over a ton per square-foot, which is much more pressure than can reasonably be applied with weights. [5-11] As with most advanced construction boat building practices, specialized training is required and techniques specific to the marine industry have evolved.

The most common use of vacuum bagging in marine construction is for bonding cores to cured laminates. This is called “dry-bagging,” as the final material is not wet-out with resin. When laminates are done under vacuum, it is called “wet-bagging,” as the vacuum lines will draw directly against reinforcements that have been wet-out with resin. For wet-bagging, a peel-ply and some means for trapping excess resin before it reaches the vacuum pump is required. [5-12]

Table 5-5 and Figure 5-32 list some materials used in the vacuum bag process. Marine industry material suppliers are an excellent source for specific product information.

Table 5-5 Materials Used for Vacuum Bagging [Marshall, Lubin]

Component	**Description**	Specific Examples
Vacuum Bag	Any airtight, flexible plastic film that won't dissolve in resin (disposable or reusable)	Visqueen, Kapton, silicone rubber, Nylon, PVA film
Breather Ply	Disposable material that will allow air to flow	Perforated Tedlar, nylon or Teflon; fabric
Bleeder Material	Material that can soak up excess resin	Fiberglass fabrics, mats; polyester mats
Peel Ply	Film directly against laminate that allows other materials to be separated after cure	Miltex; dacron release fabrics; and fiberglass fabrics
Release Film	Optionally used to release part from the mold	Perforated version of bag material
Sealing Tape	Double-sided tape or caulking material	Zinc chromate sealer tape, tube caulk
Vacuum Connection	Tubing that extends through the edge of bag	Copper or aluminum tubing with vacuum fittings

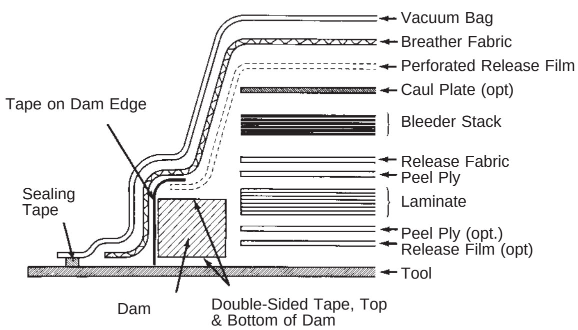


Figure 5-32 Vacuum Bag Materials for Complex Part [Marshall, *Composite Basics*]

Figure 5-33 Sealing Tape is Applied to Mold Prior to Vacuum Bag Use at Norlund Boat Company [author photo]

Figure 5-34 Overhead High- and Low-Pressure Vacuum Lines at Corsair Marine Facility [author photo]

SCRIMP^{sm}

SCRIMP^{sm} stands for "Seemann Composites Resin Infusion Molding Process." The SCRIMP^{sm} process is performed under a high vacuum, whereby all of the air is removed from constructed, pre-cut or preformed dry reinforcement materials. After this material is compacted by atmospheric pressure, a resin matrix is introduced to completely encapsulate all the materials within the evacuated area. The main difference between SCRIMP^{sm} and vacuum-bagged prepreg is that with the SCRIMP^{sm} method, the fabrics, preforms and cores are placed in the mold dry, prior to the application of any resin and a high vacuum is used to both compact the laminate and also to draw and infuse the resin into the composite. Not only is there a nil void content due to the high vacuum, but also the accurate placement of cores and selective reinforcements is enhanced by the ability to inspect the orientation of all components of the composite under vacuum without time constraints.

Figure 5-35 Dry Reinforcement In-Place for SCRIMP^{sm} Process [Mosher, TPI]

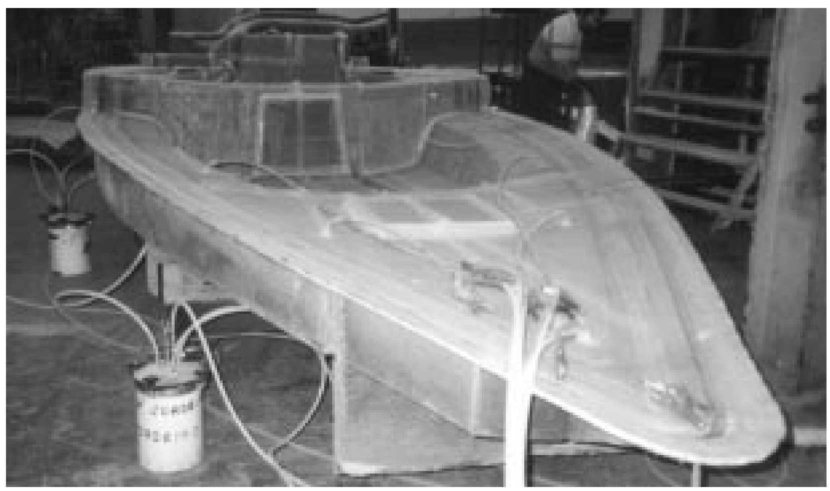


Figure 5-36 SCRIMP^{sm} Infusion Arrangement [Mosher, TPI]

Rigid open tools, such as those used for wet lay-up or vacuum bagged composites may be used as well as any specialized tooling for prepreg and autoclave processes. Since the vacuum is usually applied to only one side of the tool, no extra structural reinforcements or provisions are needed, although there are certain aspects of tooling which may be optimized for infusion. Tooling produced specifically for the infusion process can incorporate a perimeter vacuum line. When a reusable silicone bag is tailored for a high-volume part, the tool incorporates not only the vacuum channel, but it also has a seal built into the flange.

In the case of sectional molds required by hull return flanges and transom details, the separate parts of the mold can be sealed for the vacuum by sealant tape or a secondary vacuum. The mold sections are assembled before the gel coat and skin coat are applied.

In addition to the mixing equipment normally found in a composites fabrication shop, a high vacuum pump, usually a rotary vane style, is required. This is plumbed to a valved manifold with vacuum reservoirs with gauges in line. An audible leak detector is used to assure the integrity of the vacuum. Either batch mixing or in-line mixing/ metering equipment is used. [5-13]

Because reinforcement material is laid up dry and resin infusion is controlled, weight fractions to 75% with wovens and 80% with unidirectionals have been achieved. Correspondingly, tensile strengths of 87 ksi and flexural strengths of 123 ksi have been documented with E-glass in vinyl ester resin. Additional advantages of the process include enhanced quality control and reduced volatile emissions. [5-14]

Figure 5-37 SCRIMPed^{sm} U.S. Coast Guard Motor Lifeboat Built by OTECH [author photo]

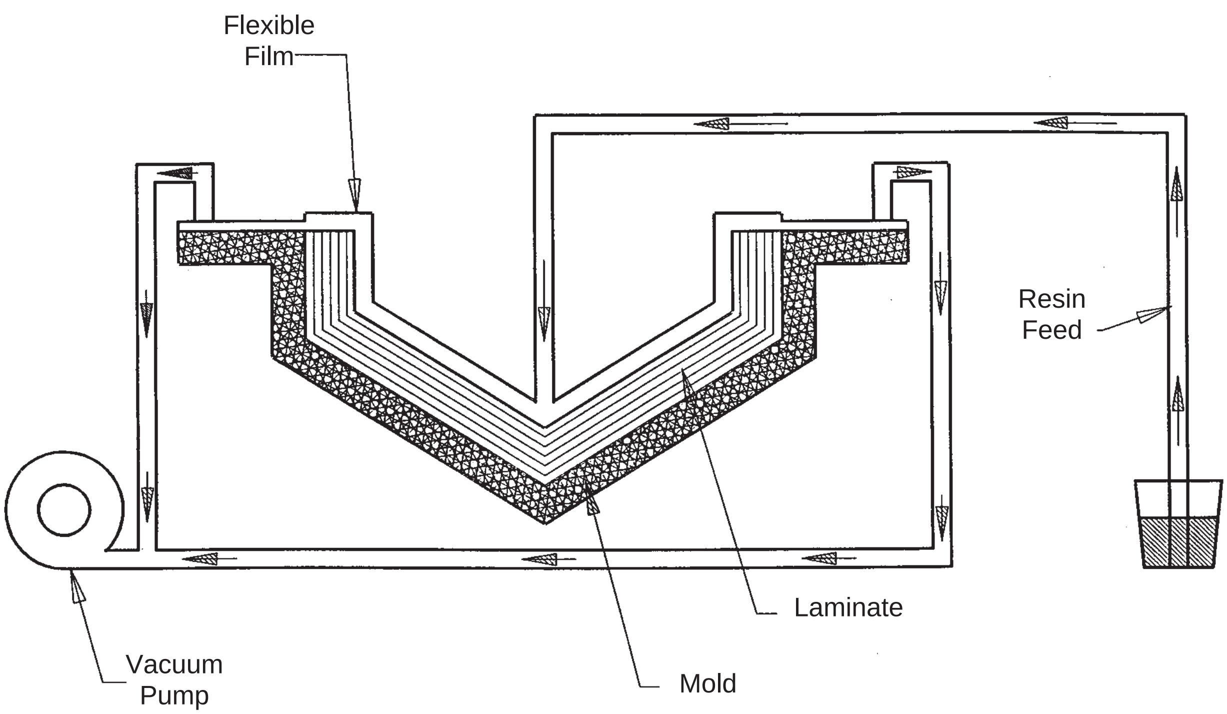


Figure 5-38 Schematic of SCRIMP^{tm} Process [Phil Mosher, TPI]

Post Curing

The physical properties of polymer laminates is very dependent upon the degree of cross-linking of the matrices during polymerization. Post curing can greatly influence the degree of cross-linking and thus the glass-transition temperature of thermoset resin systems. Some builders of custom racing yachts are post curing hulls, especially in Europe where epoxies are used to a greater extent. An epoxy such as Gougeon's GLR 125 can almost double its tensile strength and more than double ultimate elongation when cured at 250°F for three hours. [5-15]

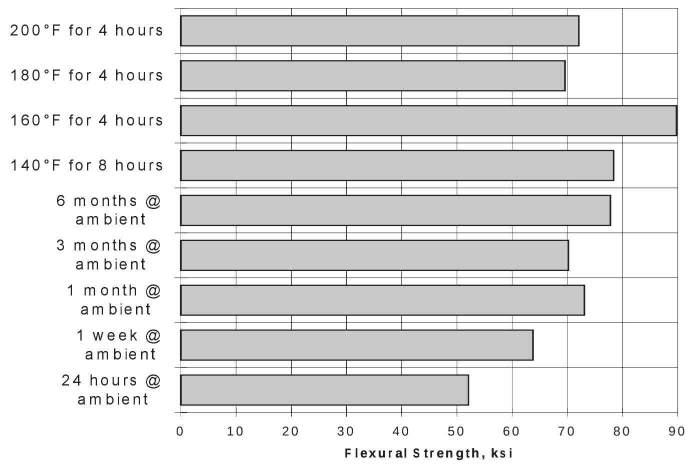


Figure 5-39 Flexural Strength of WR/DOW 510A Vinyl Ester Laminates as a Function of Postcure Conditions [Juska, 5-16]

Table 5-6 Effect of Cure Conditions on Mechanical Properties [Owens-Corning, *Postcuring Changes Polymer Properties*]

Resin System	Cure Cycle	Tensile Properties			Flexural Properties	
		Young's Modulus (x 10^6)	Ultimate Strength (psi)	Ultimate Deformation (%)	Young's Modulus (x 10^6)	Ultimate Strength (psi)
Owens-Corning E-737 Polyester/6%Cobalt/DMA /MEKP(100:2:1:2)	A	3.61	8000	7.0	2.0	7000
	B	4.80	13500	3.4	5.0	18900
	C	4.80	13400	3.4	5.0	18900
Dow 411-415 Vinyl Ester (100:0.4)	A	2.71	3000	9.0	2.8	6500
	B	2.80	3400	6.8	4.0	15600
	C	4.20	9500	4.2	4.8	17000
Dow DER-331 Epoxy/MDA (100:26.2)	D	3.72	12700	7.0	4.0	15600
	E	3.72	12700	6.5	4.1	15600
	F	4.39	13300	6.0	4.4	16200

Cure Cycles

A	24 hours @ 72°F
B	24 hours @ 72°F plus 1 hour @ 225°F
C	24 hours @ 72°F plus 2 hours @ 225°F
D	2 hours @ 250°F
E	2 hours @ 250°F plus 1.5 hours @ 350°F
F	2 hours @ 250°F plus 2.5 hours @ 350°F

Owens-Corning performed a series of tests on several resin systems to determine the influence of cure cycle on material properties. Resin castings of isophthalic polyester, vinyl ester and epoxy were tested, with the results shown in Table 5-6.

Future Trends

Prepregs

The term prepreg is short for pre-impregnated material and refers to reinforcements that already contains resin and are ready to be placed in a mold. The resin (usually epoxy) is partially cured to a "B-stage," which gives it a tacky consistency. Prepreg material must be stored in freezers prior to use and require elevated temperatures for curing. Aerospace grade prepregs also require elevated pressures achieved with an autoclave for consolidation during curing.

A handful of builders in this country use prepregs for the construction of lightweight, fast vessels. Notable applications include America's Cup sailboats and hydroplanes racing on the professional circuit. Because marine structures are quite large, curing is typically limited to oven-assisted only, without the use autoclaves. Some marine hardware and masts are made using conventional aerospace techniques.

Figure 5-40 Prepreg Material is Positioned in Mold at Ron Jones Marine [author photo]

Figure 5-41 Prepreg Material is Consolidated in Mold at Ron Jones Marine [author photo]

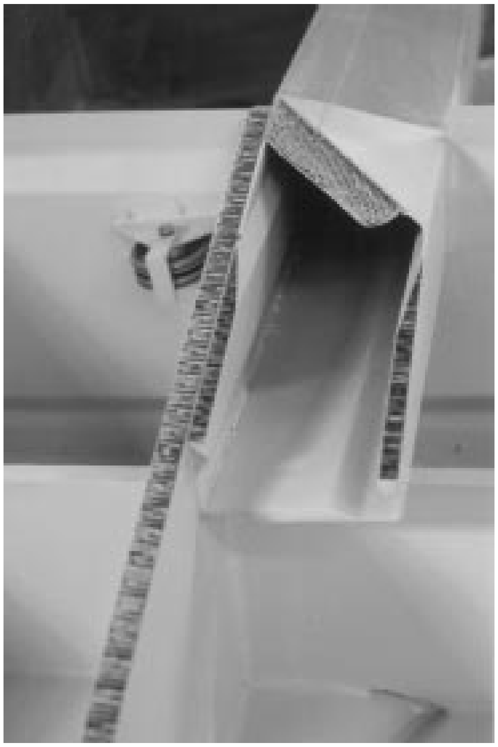


Figure 5-42 Deck Beam Showing Honeycomb Core Construction at Ron Jones Marine [author photo]

Figure 5-43 Hydroplane Hull and Cockpit Assemblies at Ron Jones Marine [author photo]

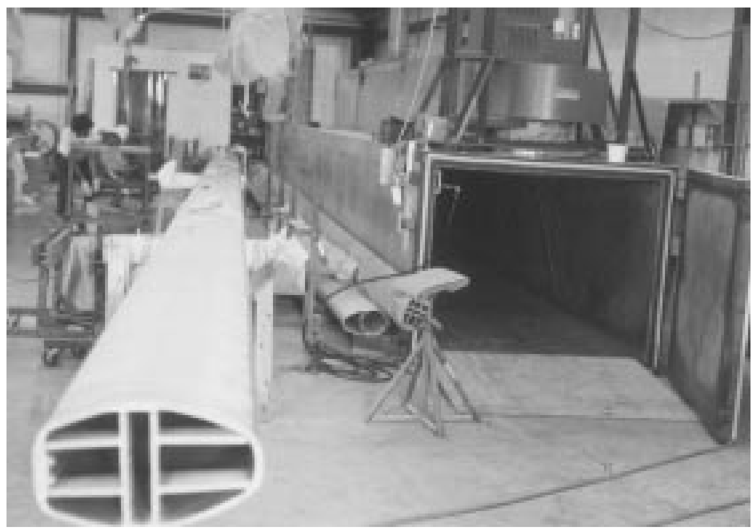


Figure 5-44 Cure Oven Used for Masts and Hardware at Goetz Marine Technology [author photo]

Prepregs are classed by the temperature at which they cure. High performance, aerospace prepregs cure at 350°F or higher and commercial prepregs cure at 250°F. A new class of "low energy cure" prepregs is emerging, with cure temperatures in the 140°F to 220°F range. These materials are particularly suited to marine construction, as curing ovens are typically temporary structures. [5-17] Eric Goetz used this method to build all of the 1995 America's Cup defenders.

Builders such as Goetz and Ron Jones who have developed techniques for fabricating marine structures with prepregs are hesitant to go back to wet lay-up methods. They cite no styrene emission, ease of handling, increased working times and higher part quality and consistency as distinct advantages. On the down side, prepreg material costs about four times as much as standard resin and reinforcement products; requires freezer storage; and must be cured in an oven. As reduced VOC requirements force builders to look for alternative construction methods, it is expected that demand will drive more prepreg manufacturers towards the development of products specifically for the marine industry.

Thick Section Prepregs

Composite Ships, Inc. of Arlington, VA is developing a prepreg process based on DSM, Italia materials that may lead to the construction of large, thick marine structures. With promising compressive strengths near 70 ksi, material costs over $5/lb are expected to be offset by the need for fewer plies and ease of fabrication.

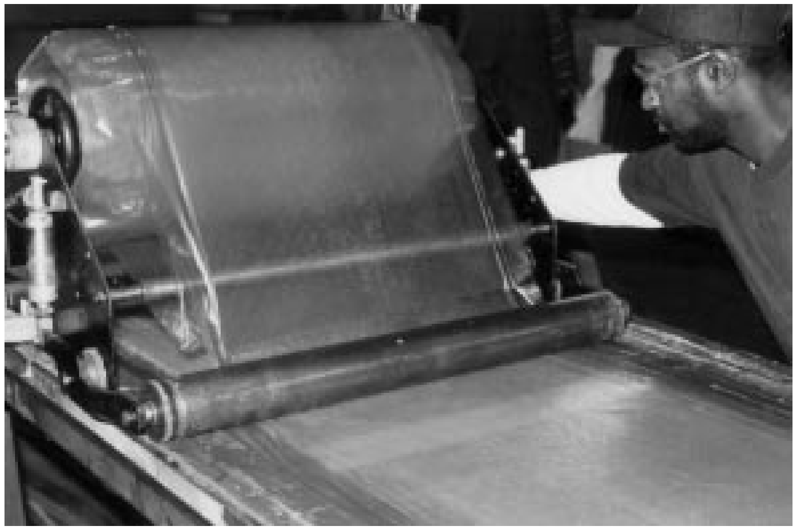


Figure 5-45 Prepreg Ply of E-Glass is Rolled Out on Consolidation Table by Composite Ships [author photo]

Figure 5-45 shows unidirectional prepreg being laid out on a preparation table. Successive plies of 0° or ±45° E-glass/epoxy are consolidated in bundles of six, with a one inch offset to create a lap joint edge. The bundled group of plies is then passed through a consolidating "wringer," as shown in Figure 5-46. The "tacky" bundle is then placed in a metal mold and "smoothed" in place. Hand consolidation with plastic putty knives to remove trapped air is assisted by the addition of some base resin, which is a B-stage epoxy.

Figure 5-46 Prepreg "Bundle" of Six Layers of Unidirectional E-Glass is Passed Through Consolidator for a Stiffener by Composite Ships [author photo]

For components such as stiffeners, the prepreg can be semi-cured at 120°F on a wood mold to create a stiff form to work with. The component is then bonded to the hull with a resin putty.

The prepreg is stored at 0°F and warmed to room temperature for one hour before use. After stabilization in the mold, the material can stay at a stabilized state for several months before the structure is cured. An entire hull structure, including semi-cured internals, is then cured in an oven built using house insulation materials. Heat is also applied to the steel mold via thermocouple feedback control. Full cure requires a temperature of 185°F for 24 hours. The U.S. Navy has sponsored the production of a half-scale Corvette midship hull section to validate the process for large ship structures.

Thermoplastic-Thermoset Hybrid Process

A company called Advance USA is currently constructing a 15 foot racing sailboat called the JY-15 using a combination of vacuum forming, injection foam and resin transfer molding. Designed by Johnstone Yachts, Inc. the boat is a very high-performance planing boat.

The hull is essentially a three-element composite, consisting of a laminated thermoplastic sheet on the outside, a polyurethane foam core and an inner skin of RTM produced, reinforced polyester. The 0.156 inch outer sheet is vacuum formed and consists of pigmented Rovel® (a weatherable rubber-styrene copolymer made by Dow Chemical and used for hot tubs, among other things) covered with a scratch resistant acrylic film and backed by an impact grade of Dow's Magnum ABS. The foam core is a two part urethane that finishes out to be about three pounds per cubic foot. The inner skin is either glass cloth or mat combined with polyester resin using an RTM process.

The hull and deck are built separately and bonded together with epoxy as shown in Figure 5-47. Although investment in the aluminum-filled, epoxy molds is significant, the builder claims that a lighter and stronger boat can be built by this process in two-thirds the time required for spray-up construction. Additionally, the hull has the advantage of a thermoplastic exterior that is proven to be more impact resistant than FRP. Closed-mold processes also produce less volatile emissions. [5-18]

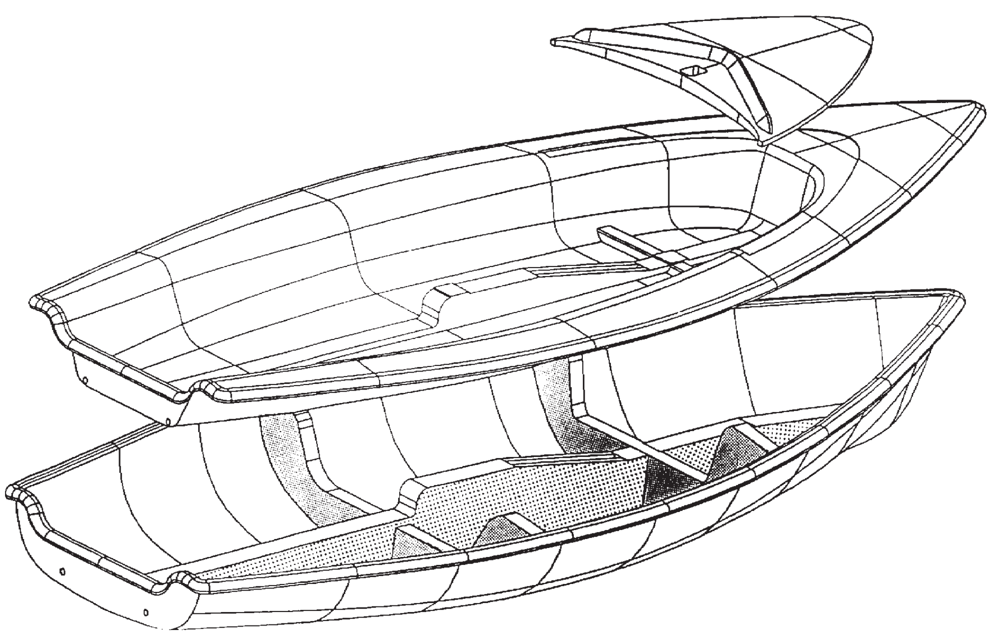


Figure 5-47 Schematic of JY-15 Showing Hull and Deck Parts prior to Joining with Epoxy [Yachting, *Yachting's 1990 Honor Roll*]

Preform Structurals

Compsys of Melbourne, FL has developed a system for prefabricating stringer systems of various geometries for production craft that contain all dry reinforcement and core material. Prisma preform systems feature a dry fiber-reinforced outer surface that is cast to shape with a two-part, self-rising urethane foam core. Sufficient reinforcement extends beyond the stringers to permit efficient tabbing to the primary hull structure. Preform stringer and bulkhead anchor systems are delivered to boat builders, where they are set in place and coated with resin simultaneously with the primary hull structure. Compsys claims that builders realize significant labor savings and improved part strength and consistency.

Figure 5-48 Two-Part Expansion Foam is Injected into Stringer Molds at Compsys with Careful Monitoring of Material Flow rate and Duration [author photo]

UV-Cured Resin

Ultra violet (UV) cured resin technology, developed by BASF AG, has been available in Europe for the past 10 years, and is being promoted in the U.S. by the Sunrez^{tm} Corporation of El Cajun, CA. The technology promises long pot life and rapid curing of polyester and vinyl ester laminates.

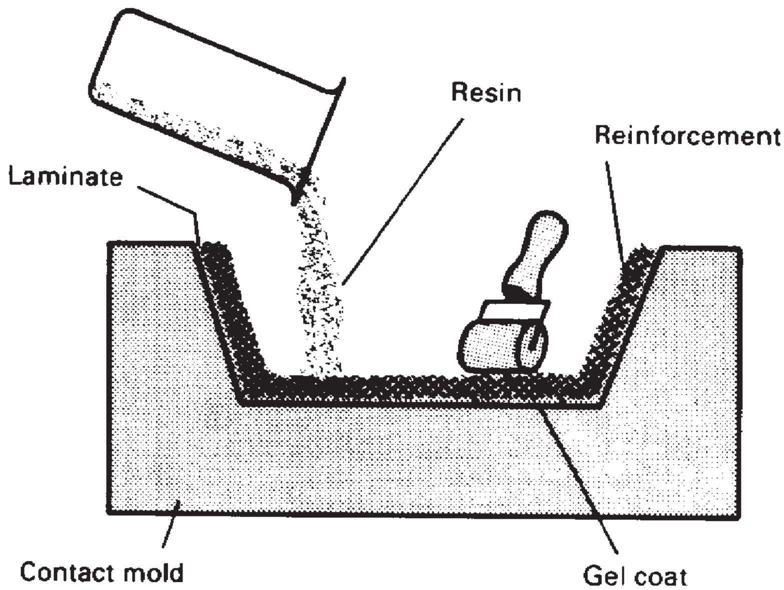
Figure 5-49 One-Half Scale Corvette Hull Test Section Built for the U.S. Navy Using the Sunrez^{tm} Process [author photo]

Ten years ago, BASF developed a light initiator for rapid curing of polyester and vinyl ester resins at their laboratories in West Germany. Total cure times of 3 minutes are typical for parts of 3/16" and under 10 minutes for parts 1/2" thick, using open molds and hand or machine application of the resin and glass. Sunrez^{tm} also claims that styrene emissions can be reduced by up to 95% depending on the fabrication method used. (This is based on a fabrication process patented by Sunrez^{tm}).

A BASF photo-initiator is added to a specially formulated version of a fabricator's resin and is shipped in drums or tanker to the shop. The resin is drawn off and used without the addition of a catalyst. The part is laminated normally and any excess resin is saved for the next part. When the laminator feels that he has completed the laminate, the part is exposed to UV light, and cured in 3 to 5 minutes. [5-19]

HAND LAY-UP

A contact mold method suitable for making boats, tanks, housings and building panels for prototypes and other large parts requiring high strength. Production volume is low to medium.



Process Description

A pigmented gel coat is first applied to the mold by spray gun for a high-quality surface. When the gel coat has become tacky, fiberglass reinforcement (usually mat or cloth) is manually placed on the mold. The base resin is applied by pouring, brushing or spraying. Squeegees or rollers are used to consolidate the laminate, thoroughly wetting the reinforcement with the resin, and removing entrapped air. Layers of fiberglass mat or woven roving and resin are added for thickness.

Catalysts and accelerators are added to the resin to cure without external heat. The amounts of catalyst and accelerator are dictated by the working time necessary and overall thickness of the finished part.

The laminate may be cored or stiffened with PVC foam, balsa and honeycomb materials to reduce weight and increase panel stiffness.

Resin Systems

General-purpose, room-temperature curing polyesters which will not drain or sag on vertical surfaces. Epoxies and vinyl esters are also used.

Molds

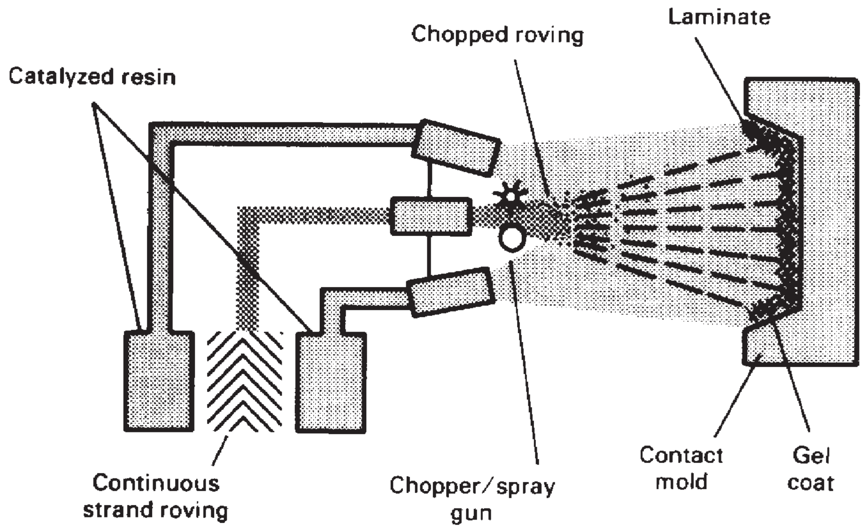
Simple, single-cavity, one-piece, either male or female, of any size. Vacuum bag or autoclave methods may be used to speed cure, increase fiber content and improve surface finish.

Major Advantages

Simplest method offering low-cost tooling, simple processing and a wide range of part sizes. Design changes are readily made. There is a minimum investment in equipment. With good operator skill, good production rates and consistent quality are obtainable.

SPRAY-UP

A low-to-medium volume, open mold method similar to hand lay-up in its suitability for making boats, tanks, tub/shower units and other simple medium to large size shapes such as truck hoods, recreational vehicle panels and commercial refrigeration display cases. Greater shape complexity is possible with spray-up than with hand lay-up.



Process Description

Fiberglass continuous strand roving is fed through a combination chopper and spray gun. This device simultaneously deposits chopped roving and catalyzed resin onto the mold. The laminate thus deposited is densified with rollers or squeegees to remove air and thoroughly work the resin into the reinforcing strands. Additional layers of chopped roving and resin may be added as required for thickness. Cure is usually at room temperature or may be accelerated by moderate application of heat.

As with hand lay-up, a superior surface finish may be achieved by first spraying gel coat onto the mold prior to spray-up of the substrate. Woven roving is occasionally added to the laminate for specific strength orientation. Also, core materials are easily incorporated.

Resin Systems

General-purpose, room-temperature curing polyesters, low-heat-curing polyesters.

Molds

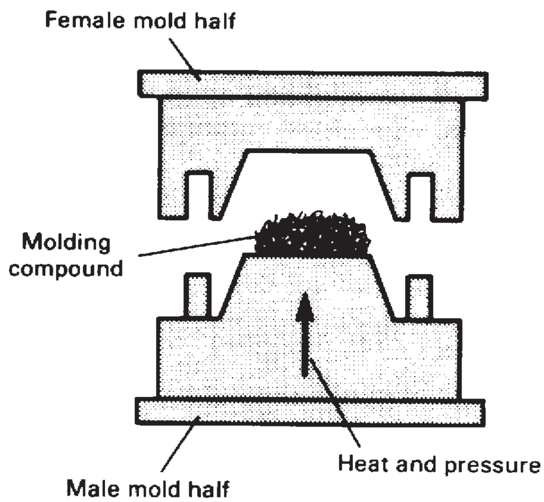
Simple, single-cavity, usually one-piece, either male or female, as with hand lay-up molds. Occasionally molds may be assembled, which is useful when part complexity is great.

Major Advantages

Simple, low-cost tooling, simple processing; portable equipment permits on-site fabrication; virtually no part size limitations. The process may be automated.

COMPRESSION MOLDING

A high-volume, high-pressure method suitable for molding complex, high-strength fiberglass-reinforced plastic parts. Fairly large parts can be molded with excellent surface finish. Thermosetting resins are normally used.



Process Description

Matched molds are mounted in a hydraulic or mechanical molding press. A weighed charge of sheet or bulk molding compound, or a "preform" or fiberglass mat with resin added at the press, is placed in the open mold. In the case of preform or mat molding, the resin may be added either before or after the reinforcement is positioned in the mold, depending on part configuration. The two halves of the mold are closed, and heat (225 to 320°F) and pressure (150 to 2000 psi) are applied. Depending on thickness, size, and shape of the part, curing cycles range from less than a minute to about five minutes. The mold is opened and the finished part is removed. Typical parts include: automobile front ends, appliance housings and structural components, furniture, electrical components, business machine housings and parts.

Resin Systems

Polyesters (combined with fiberglass reinforcement as bulk or sheet molding compound, preform or mat), general purpose flexible or semi-rigid, chemical resistant, flame retardant, high heat distortion; also phenolics, melamines, silicones, dallyl phtalate, and some epoxies.

Molds

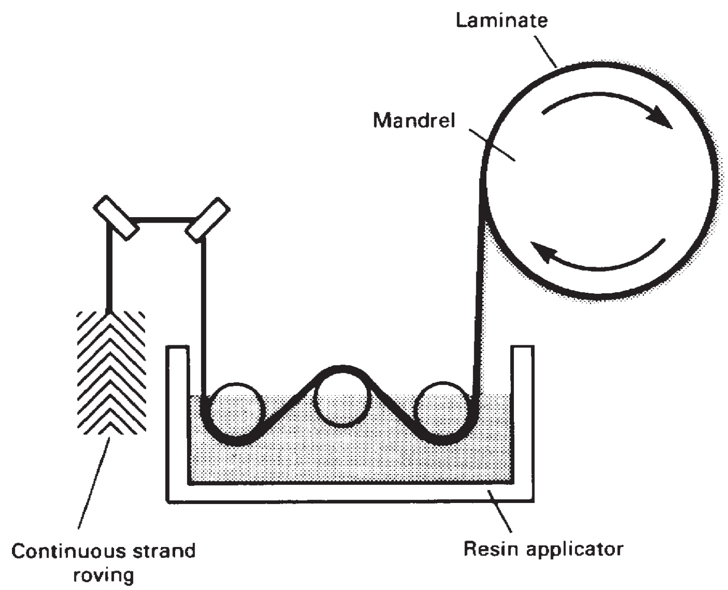
Single- or multiple-cavity hardened and chrome plated molds, usually cored for steam or hot oil heating: sometimes electric heat is used. Side cores, provisions for inserts, and other refinements are often employed. Mold materials include cast of forged steel, cast iron, and cast aluminum.

Major Advantages

Highest volume and highest part uniformity of any thermoset molding method. The process can be automated. Great part design flexibility, good mechanical and chemical properties obtainable. Inserts and attachments can be molded in. Superior color and finish are obtainable, contributing to lower part finishing cost. Subsequent trimming and machining operations are minimized.

FILAMENT WINDING

A process resulting in a high degree of fiber loading to provide extremely high tensile strengths in the manufacture of hollow, generally cylindrical products such as chemical and fuel storage tanks and pipe, pressure vessels and rocket motor cases.



Process Description

Continuous strand reinforcement is utilized to achieve maximum laminate strength. Reinforcement is fed through a resin bath and wound onto a suitable mandrel (pre-impregnated roving may also be used). Special winding machines lay down continuous strands in a predetermined pattern to provide maximum strength in the directions required. When sufficient layers have been applied, the wound mandrel is cured at room temperature or in an oven. The molding is then stripped from the mandrel. Equipment is available to perform filament winding on a continuous basis.

Resin Systems

Polyesters and epoxies.

Molds

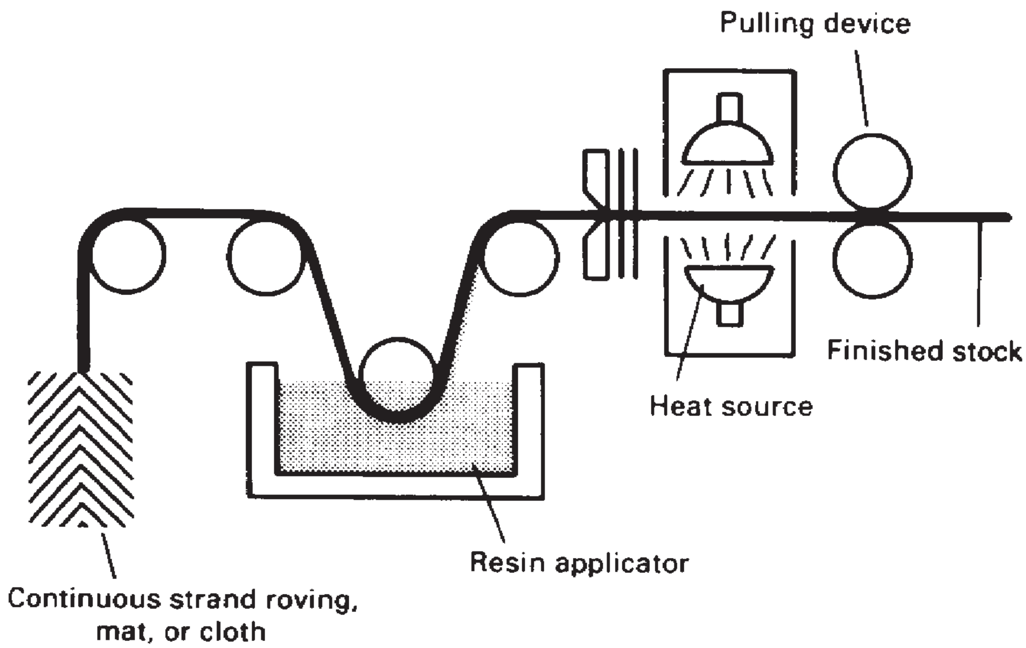
Mandrels of suitable size and shape, made of steel or aluminum form the inner surface of the hollow part. Some materials are collapsible to facilitate part removable.

Major Advantages

The process affords the highest strength-to-weight ratio of any fiberglass reinforced plastic manufacturing practice and provides the highest degree of control over uniformity and fiber orientation. Filament wound structures can be accurately machined. The process may be automated when high volume makes this economically feasible. The reinforcement used is low in cost. Integral vessel closures and fittings may be wound into the laminate.

PULTRUSION

A continuous process for the manufacture of products having a constant cross section, such as rod stock, structural shapes, beams, channels, pipe, tubing and fishing rods.



Process Description

Continuous strand fiberglass roving, mat or cloth is impregnated in a resin bath, then drawn through a steel die, which sets the shape of the stock and controls the fiber/resin ratio. A portion of the die is heated to initiate the cure. With the rod stock, cure is effected in an oven. A pulling device establishes production speed.

Resin Systems

General-purpose polyesters and epoxies.

Molds

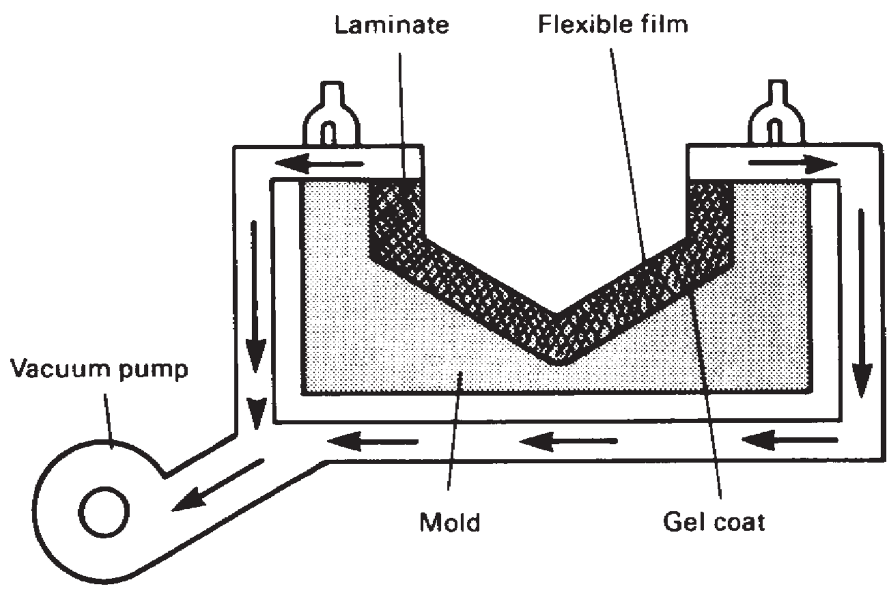
Hardened steel dies.

Major Advantages

The process is a continuous operation that can be readily automated. It is adaptable to shapes with small cross-sectional areas and uses low cost reinforcement. Very high strengths are possible due to the length of the stock being drawn. There is no practical limit to the length of stock produced by continuous pultrusion.

VACUUM BAG MOLDING

Mechanical properties of open-mold laminates can be improved with a vacuum-assist technique. Entrapped air and excess resin are removed to produce a product with a higher percentage of fiber reinforcement.



Process Description

A flexible film (PVA or cellophane) is placed over the completed lay-up, its joint sealed, and a vacuum drawn. A bleeder ply of fiberglass cloth, non-woven nylon, polyester cloth or other absorbent material is first placed over the laminate. Atmospheric pressure eliminates voids in the laminate, and forces excel resin and air from the mold. The addition of pressure further results in high fiber concentration and provides better adhesion between layers of sandwich construction. When laying non-contoured sheets of PVC foam or balsa into a female mold, vacuum bagging is the technique of choice to ensure proper secondary bonding of the core to the outer laminate.

Resin Systems

Polyesters, vinyl esters and epoxies.

Molds

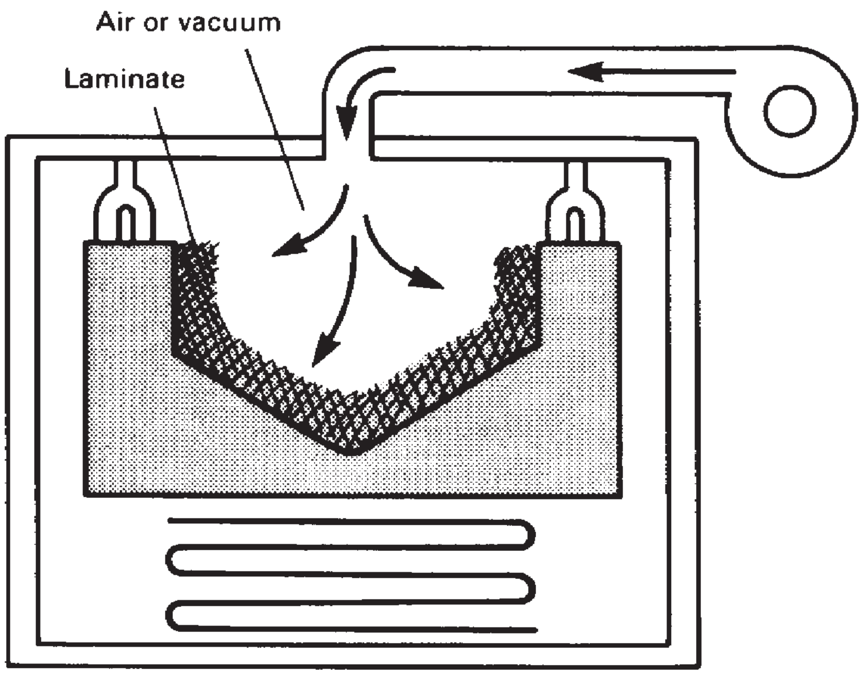
Molds are similar to those used for conventional open-mold processes.

Major Advantages

Vacuum bag processing can produce laminates with a uniform degree of consolidation, while at the same time removing entrapped air, thus reducing the finished void content. Structures fabricated with traditional hand lay-up techniques can become resin rich, especially in areas where puddles can collect. Vacuum bagging can eliminate the problem of resin rich laminates. Additionally, complete fiber wet-out can be accomplished when the process is done correctly. Improved core-bonding is also possible with vacuum bag processing.

AUTOCLAVE MOLDING

A pressurized autoclave is used for curing high-quality aircraft components at elevated temperatures under very controlled conditions. A greater laminate density and faster cure can be accomplished with the use of an autoclave.



Process Description

Most autoclaves are built to operate above 200°F, which will process the 250 to 350°F epoxies used in aerospace applications. The autoclaves are usually pressurized with nitrogen or carbon dioxide to reduce the fire hazard associated with using shop air. Most autoclaves operate at 100 psi under computer control systems linked to thermocouples embedded in the laminates.

Resin Systems

Mostly epoxies incorporated into prepreg systems and high-temperature aerospace systems.

Molds

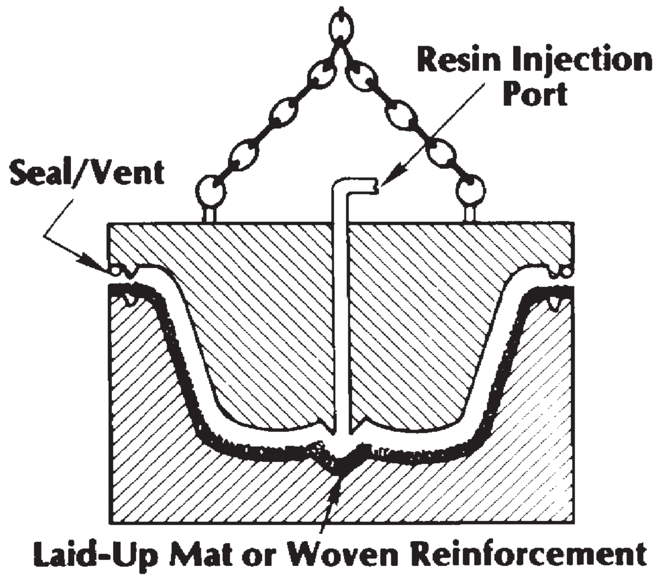
Laminated structures can be fabricated using a variety of open- or close-mold techniques.

Major Advantages

Very precise quality control over the curing cycle can be accomplished with an autoclave. This is especially important for high temperature cure aerospace resin systems that produce superior mechanical properties. The performance of these resin systems is very much dependent on the time and temperature variables of the cure cycle, which is closely controlled during autoclave cure.

RESIN TRANSFER MOLDING

Resin transfer molding is an intermediate-volume molding process for producing reinforced plastic parts and a viable alternative to hand lay-up, spray-up and compression molding.



Process Description

Most successful production resin transfer molding (RTM) operations are now based on the use of resin/catalyst mixing machinery using positive displacement piston-type pumping equipment to ensure accurate control of resin to catalyst ratio. A constantly changing back pressure condition exists as resin is forced into a closed tool already occupied by reinforcement fiber.

The basic RTM molding process involves the connection of a meter, mix and dispense machine to the inlet of the mold. Closing of the mold will give the predetermined shape with the inlet injection port typically at the lowest point and the vent ports at the highest.

Resin System

Polyesters, vinyl esters, polyurethanes, epoxies and nylons.

Molds

RTM can utilize either “hard” or “soft” tooling, depending upon the expected duration of the run. Hard tooling is usually machined from aluminum while soft tooling is made up of a laminated structure, usually epoxy.

Major Advantages

The close-mold process produces parts with two finished surfaces. By laying up reinforcement material dry inside the mold, any combination of materials and orientation can be used, including 3-D reinforcements. Part thickness is also not a problem as exotherm can be controlled. Carbon/epoxy structures up to four inches thick have been fabricated using this technique.

Repair

Failures in FRP constructed vessels fall into one of two categories. First, the failure can be the result of a collision or other extreme force. Secondly, the failure may have occurred because of design inadequacies. In the case of the latter, the repair should go beyond restoring the damaged area back to its original strength. The loads and stress distributions should be reexamined to determine proper design alterations. When the failure is caused by an unusual event, it should be kept in mind that all repair work relies on secondary bonding, which means that stronger or additional replacement material is needed to achieve the original strength. In general, repair to FRP vessels can be easier than other materials. However, proper preparation and working environment are critical. The following is a summary of work done for the Navy by Kadala and Gregory.

Repair in Single-Skin Construction

This section is applicable for repairs ranging from temporary field repairs to permanent structural repairs performed in a shipyard. General guidance related to inspections, material selection, repair techniques, quality control, and step-by-step repair procedures are provided. The repair methods are based on well established procedures commonly used in commercial GRP boat fabrication and repair [5-20 through 5-30]. The guidance and procedures set forth here, along with the information provided in the supplemental reference documents, should provide the necessary basic information required to perform GRP repairs. Since the level of complexity of each repair situation is different, careful planning and tailoring of these procedures is expected.

Type of Damage

Surface Damage

Cracks, crazing, abrasions, and blisters are common types of GRP damage which are characterized by a depth typically less than 1/16" (2 mm), where the damage does not extend into the primary reinforcement. This damage has no structural implications by itself; however, if unattended, it can cause further damage by water intrusion and migration. Crazing may indicate the presence of high stress or laminate damage below the surface. (see Figure 5-50)

Laminate Damage

Extreme loadings may result in cracks, punctures, crushing, and delaminations in the GRP primary glass reinforcement. Delaminations often initiate at structural discontinuities due to out-of-plane stresses. For establishing repair procedures, this damage is categorized into two classes: partially-through thickness, and through thickness damage. (see Figure 5-51)

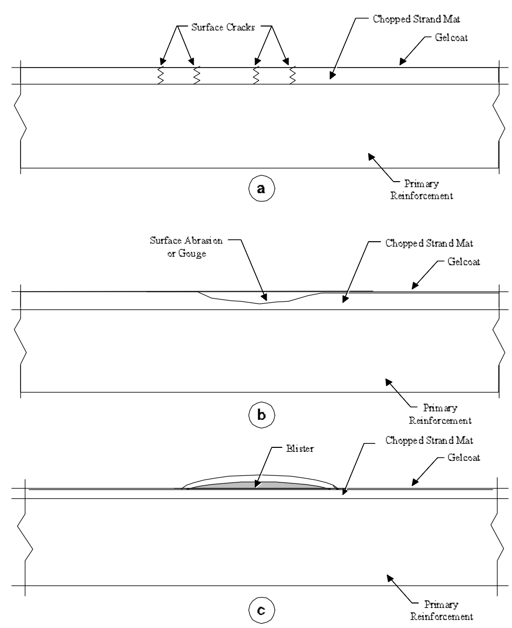


Figure 5-50 Damage: Surface Cracks, Gouges, Abrasions, and Blisters

Tabbed Joint Delamination

Connection such as at bulkheads or deck to the shell is accomplished with laminated tabbed joints consisting of successive plies of overlapping glass reinforcement, as shown in Figure 5-52. The tabbed joint forms a secondary bond with the structural components being joined, since the components are usually fully cured when connected. Because the geometry of tabbed joints tends to create stress concentrations, they are susceptible to delaminating and peel.

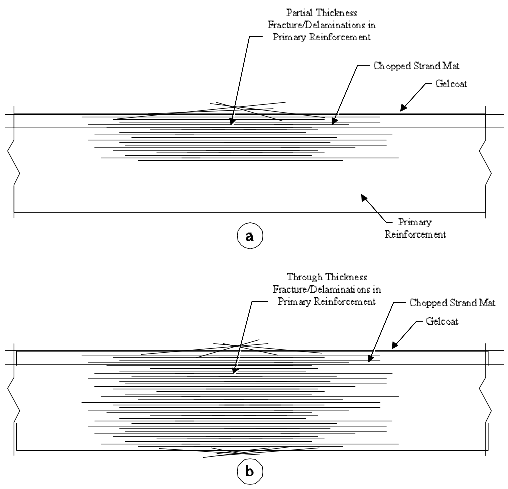


Figure 5-51 Damage: Laminate Cracks, Fractures, Punctures, Delaminations

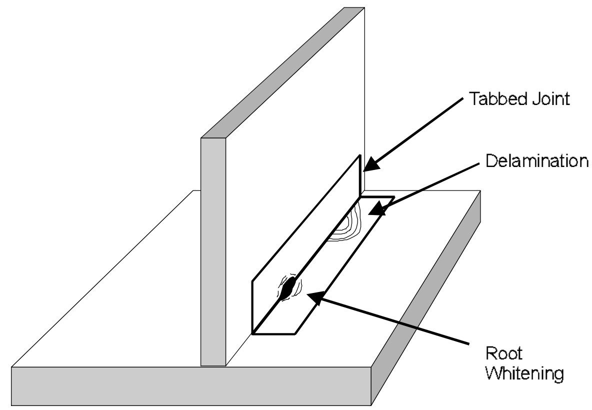


Figure 5-52 Damage: Tabbed Joint Connection

Selection of Materials

Resin

The integrity of the repair will depend on the secondary bond strength of the resin to the existing laminate. When a laminate cures, the resin molecules crosslink to form strong, three-dimensional polymer networks. When laminating over a cured laminate, the crosslinking reaction does not occur to a significant degree across the bondline, so the polymer networks are discontinuous and the bond relies on the adhesive strength of the resin. In general, isophthalic polyester, vinyl ester, or epoxy resins are preferred for GRP repairs and alterations. General purpose (GP) resins are less desirable. When considering strength, cost and ease of processing, isophthalic polyester and vinyl ester resins are recommended, although epoxy laminates are generally stronger. Epoxy resins are highly adhesive and have longer shelf lives than polyesters and vinyl esters, which makes them ideal for emergency repair kits. However, they are intolerant of bad mix ratios and polyesters and vinyl esters do not bond well to epoxies. Therefore, any further rework to an epoxy repair will have to be made with an epoxy.

Glass Reinforcement

If practicable, the original primary glass reinforcement shall be used in the repair, especially if the part is heavily loaded and operating near its design limits. If an alternative reinforcement is selected, it should be similar in type to that being repaired. Lighter weight reinforcements can be used in shallow repairs where it is desirable to have multiple layers of thinner reinforcement instead of one or two thick layers.

General Repair Procedures

Damage Assessment

Visual, probing, and hammer sounding are three techniques suitable for inspecting damage. Most damage is found visually and is evident from indicators such as:

- Cracked or chipped paint or abrasion of the surface;
- Distortion of a structure or support member;
- Unusual buildup or presence of moisture, oil, or rust;
- Structure that appears blistered or bubbled and feels soft to the touch;
- Surface and penetrating cracks, open fractures and exposed fibers;
- Gouges; and
- Debonding of joints.

Inspection of GRP structure may require the removal of insulation, outfitting or equipment to obtain a better view of the damage. The site should be thoroughly cleaned. The damaged area should be further investigated by probing or hammer sounding to determine its extent. Paint can also be removed from the laminate to aid the visual inspection.

Probing

Probing a surface defect (crack, edge delamination, etc.) with a sharp spike, knife, or ruler can provide further indication of the physical dimensions and characteristics of a defect. For tight cracks, a guitar string or feeler gage can be used. An apparent crack along the surface may actually be the edge of a much larger delamination.

Hammer Sounding

Hammer sounding is a very effective way to detect debunks and delaminations in a GRP laminate. Sounding involves striking the area of concern repeatedly with a hammer. Undamaged regions should be sounded to establish a contrast between damaged and undamaged laminate. Make sure the contrast in sound is not due to physical features of the structure, such as a stiffener on the far side. An undamaged laminate produces a dull sound when struck, while debunks and delaminations tend to ring out louder. By placing your hand on the surface being sounded, it is possible to feel the damaged laminate vibrate when struck. The extent of damage can be fairly accurately determined by hammer sounding. The damaged region should be clearly marked with a permanent ink or paint pen.

Water Contaminated Laminates

If the contamination is from salt water, thoroughly rinse the area with fresh water. Let the area dry for a minimum of 48 hours. Heat lamps, hair dryers, hot air guns and industrial hot air blowers can be used to speed up the drying process. Use fans to circulate the air in confined or enclosed areas. The GRP can be monitored with a moisture meter or core samples can be drilled. The moisture content of a saturated composite laminate can reach 3% by weight. Repair work should not begin until the moisture content is 0.5% by weight or less.

Wiping the surface with acetone will enhance the ability of the styrene in the laminating resin to penetrate the air-inhibited surface of the cured laminate. The acetone will produce a tacky surface on the existing laminate; however, it is recommended not to laminate on this surface. As long as the surface is tacky, acetone is still present. The acetone must be allowed to evaporate prior to lamination (1 to 3 minutes). The tack is lost as the acetone evaporates.

Compressed air should not be used to clean the area being repaired as it may deposit oil, water, or other contaminants onto the surface and disperse fiberglass dust throughout the compartment.

Removal of Damage

Precautions should be taken to minimize the dispersion of fiberglass dust. Vacuum shrouded tools should be employed, and if necessary, the work site enclosed. Fiberglass dust is abrasive and can damage mechanical equipment. Once the damaged area has been determined and marked, the damaged GRP can be removed as follows:

For damage extending partially through the thickness, the damaged GRP can be removed using a grinder with a 16-40 grit disk. The damaged area can be smoothed and shaped using a 60-80 grit disk. For extensive GRP removal, grinding is inefficient and will generate a significant amount of fiberglass dust, thus an alternative method for GRP removal is suggested. Make close perpendicular cuts into the laminate using a circular saw with a diamond grit or masonry blade or using a die grinder with a 1-1/2" - 2" cutting wheel. The cuts should extend to the depth of damage. The damaged laminate can then be undercut and removed with a wood chisel or a wide blade air chisel can be employed to peel the damaged plies away. A laminate peeler can efficiently remove gel coat and GRP laminate while greatly reducing airborne dust and particulate matter. They can cut up to a ¼" (6 mm) of laminate per pass, leaving a faired surface. Figure 5-53 shows a "peeler" developed by Osmotech, Inc.

Figure 5-53 Laminate Peeler Developed by Osmotech with a Thick-Sectioned Laminate After One Pass [author photo]

For damage extending through the thickness, the damaged GRP can be removed using a circular saw or Sawz-all.

Lay-Up Scheme

Two different schemes can be used to lay-up primary reinforcement on tapered scarf joints. One scheme, as shown in Figure 5-54a, is to lay-up the smallest ply first with each successive ply being slightly larger. The plies should butt up to the scarf. Each ply should be cut slightly oversized so that it can be trimmed as it is being laminated in place. Avoid using undersized plies, as this would create a resin rich pocket along the bond line resulting in a weaker joint. A second scheme is to lay the plies parallel to the scarf as shown in Figure 5-54b. This approach tends to require more finishing work to blend the repair into the existing laminate. Fiber orientation should be maintained when laying up the glass reinforcement. It has been shown that lightly loaded parts can be repaired with reinforcements of equal size that correspond to the size of the damaged area. The repair is then ground flush to resemble Figure 5-54b.

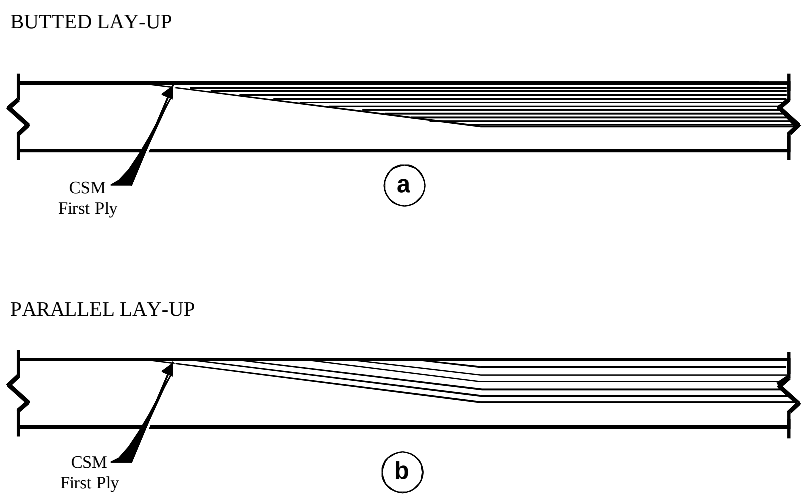


Figure 5-54 Lay-up Schemes

Ply Overlap Requirements

Adjacent pieces of glass reinforcement are to be either overlapped or butt jointed, depending on whether there is a selvage edge. Selvage edges, (a narrow edge along the length of the reinforcement containing only weft fibers to prevent raveling) should be overlapped, otherwise the reinforcement edges should butt. Edge joints in successive layers should be offset 6" (150 mm) relative to the underlying ply. Lengthwise joints in successive layers should be staggered by 6" (150 mm). The ply overlap should be 1" (25 mm). Figure 5-55 illustrates the overlap requirements.

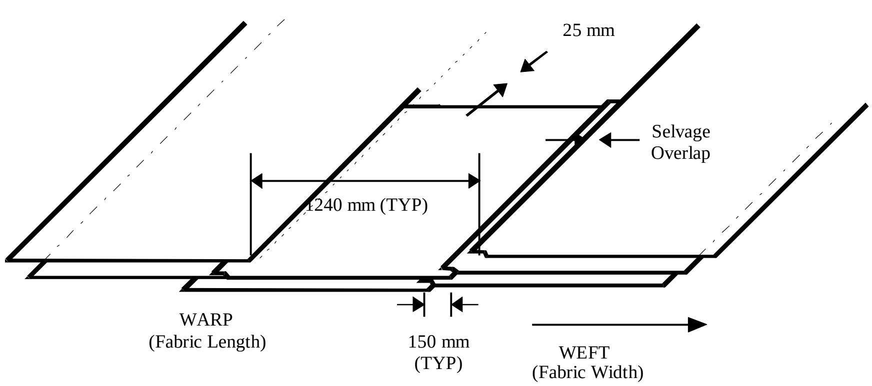


Figure 5-55 Ply Overlap Requirements

Lay-Up Process

Repairs to marine composite structures can generally be accomplished using a wet lay-up approach, laminating the repair “in-situ”. The general approach is to apply a portion of the resin onto the prepared surface and then work the glass reinforcement into the resin. This approach will decrease the chance for entrapping air beneath the plies. Resin applied to dry glass will inevitably result in air bubble problems. The reinforcement may be applied dry or partially saturated with resin. Each ply should be completely wet-out and consolidated with small ridge rollers, eliminating any air bubbles and excess resin before the next ply is added. This approach is continued, always working the reinforcement into the resin and following the specific lay-up scheme until the laminate is built-up to the desired thickness.

When laminating on inclined and overhead surfaces, it maybe helpful to pre-saturate small pieces of glass reinforcement on a pasteboard, then apply the reinforcement to the resin wet surface. Another technique suited for large overhead areas is to roll up the dry reinforcement on a cardboard tube, wet-out the area being patched and start to roll out the reinforcement over the resin wet area. While one person holds the reinforcement, another rolls resin into it. If the reinforcement is wet-out as it is applied, the suction of the wet resin will hold it in place. The key is to not let the edges of the reinforcement fall.

The first reinforcement ply laid up should be chopped strand mat (CSM). For tapered scarf joints, the mat should cover the entire faying surface. This will improve the interlaminar bond with the existing laminate. The number of layers which can be laid at one time is dependent on the resin being used, the size of the repair and the surrounding temperature. Laminating too many layers over a large area near the resin’s upper working temperature may cause excess exotherm and “cook” the resin, causing it to become weak and brittle. Rapid curing may also occur which tends to cause excessive shrinkage. As a general rule, a cumulative thickness of approximately 1/4" (6 mm) is the maximum that should be laminated at one time. More plies can be layed-up under cool conditions and working in a small area, where the laminate mass is small or where the heat generated can readily dissipate into the surrounding,

Laminate Quality Requirements

The repair should be inspected prior to painting and the following should not be observed:

- No open voids, pits, cracks, crazing, delaminations or embedded contaminates in the laminate;
- No evidence of resin discoloration or other evidence of extreme exotherm;
- No evidence of dry reinforcement as shown by a white laminate; and
- No wrinkles in the reinforcement and no voids greater than ½" (12 mm). (Voids greater than ½" (12 mm) should be repaired by resin injection. Two 3/16" (5 mm) diameter holes can be drilled into the void; one for injecting resin and the other to let air escape and verify that hole is filled).

The surface of the repair should be smooth and conform to the surrounding surface contour. The degree of cure of the repaired laminate should be within 10% of the resin manufacturer’s specified value, as measured by a Barcol Hardness test.

Table 5-7 Minor Surface Damage

Surface Damage	Damage w/o Mat Replacement	Damage Requiring Mat Replacement	Blisters
For damage depicted in Figure 5-50, clean the damaged area of any dirt or oil prior to sanding. For surface cracks, gel coat crazing and abrasions, remove the damage using a disk sander or grinder with a 60 grit disk. To avoid gouges, hold the grinder at a low angle (5° -10°). Do not penetrate into the primary reinforcement. Taper the edges to a slope of approximately 12:1 as shown in Figure 5-54a. Remove at least 2" (50 mm) of paint and primer from around the edges of the ground out area using a 60 grit disk, being careful not to grind away the gel coat.	Prepare the damaged area as per procedure outlined for Surface Damage. Carefully fill the depression with gel coat putty or a suitable filler using a squeegee or putty knife, working out any air bubbles. The area should be filled slightly above the original surface to allow for shrinkage and surface fairing. The putty can be covered with release film, such as PVA (sheet form) or cellophane and the surface squeegeed, working out entrapped air as it is being covered. The release film will provide a smooth surface and act as an air barrier for putties made with an air-inhibited gel coat. PVA can also be sprayed to ensure a tack free cure. Leave the release film in place until the putty has fully cured.	Prepare the damaged area as per procedure outlined for Surface Damage. Template the ground out area and cut the CSM layer(s) from the template as per Figure 5-57. Prepare the resin according to manufacturer's specifications. Coat the repair surface with resin and apply the CSM layer(s) working out any air bubbles with the roller, brush or squeegee. Release film or peel ply can be applied to help fair the repair into the existing laminate surface thereby reducing the amount of sanding required. After the patch has cured remove the film and sand the patch with 80 to 120 grit so that it is faired into the laminate. There should not be any exposed fibers.	If the blistering is concentrated and covers a large area, complete removal of the paint and gel coat from the effected areas may be required. An efficient way to remove gel coat is to utilize a gel coat peeler. Peelers leave a relatively smooth surface requiring less fairing than a ground surface and waste is easier to manage. After the gel coat is removed, inspect the layers below to determine the extent of damage. If the backup CSM is severely damaged, it should be ground or peeled away down to the primary reinforcement. Figure 5-53 depicts a gel coat blister. Deeper blisters require the removal of reinforcement layers. Specialized tools, such as that shown in Figure 5-53 have been developed for this purpose.
Thin scratches and gouges can be removed using a drill with a burr or sanding sleeve or a die grinder, forming a V-groove along the length of the flaw. Feather the edges of the "V" to the existing laminate using a 100 grit disk to provide a bonding surface for gel coat putty or suitable filler. Remove paint from the area using a 60 grit disk.	After hardening, peel off the release film if used or remove the PVA by washing the surface thoroughly with water. Using a sanding block with 80 to 120 grit sand paper, sand the repair feathering it into the surrounding surface. Be careful not to sand through the gel coat of the surrounding laminate. Inspect the surface for depressions, voids, pits, porosity and exposed fibers. If any of these flaws exist repair them using the above steps.	Thoroughly vacuum the area and wipe down with acetone. Using a squeegee or putty knife, apply gel coat putty or other suitable compound to refine the shape of the patch closer to the surface contour. Release film can be applied to help in fairing the patch. Thoroughly vacuum the area and wipe with acetone. Inspect the repair in accordance with QA requirements	Examine the hull and mark the blisters. Clean the affected area of all marine growth and contaminants like grease or oil.
Vacuum the dust and wipe down the area with acetone There are many "off-the-shelf" pastes, putties and fillers formulated for marine uses that are suitable for surface repairs. One such product is Poly-Fair R26. Note that auto body filler should not be used since it is more susceptible to moisture absorption. Gel coat putty can also be formulated on site by thickening the gel coat with Cab-O-Sil.	Thoroughly vacuum and wipe down the area with acetone. Inspect the repair in accordance with Quality Assurance requirements.	Allow the putty to completely cure. Remove the release film if used. Using 80 to 120 grit sandpaper, sand the patch until it blends into the surrounding surface. Be careful not to remove the gel coat from the surrounding surface. Inspect the surface for depressions, voids, pits, porosity and exposed fibers. If any of these flaws exist repair them using the above steps.	Using caution, puncture the surface of the blisters with a chisel point and allow the acidic fluid to drain. Remove the blistered laminate with a grinder and a 60 grit disk. Bevel the edge of the repair area to a 12:1 angle to provide a greater bonding area. Do not grind or drill deeper than necessary. For small blisters, use a countersink bit to open up the blister.
	Apply primer and paint in accordance with the manufacturer's specifications.	Prepare the gel coat according to manufacturers specifications. Catalyze 20% more than is needed to cover the repair, to account for wastage. On small areas, apply the gel coat with a brush or roller. Spray equipment is recommended for large areas for a more uniform application. The gel coat should be applied in multiple passes, each depositing a thin continuous film until a thickness of between 20 to 30 mils is obtained. The gel coat should not gel between passes. Use a wet film thickness gauge to verify the thickness.	The surface should be steam cleaned, pressure washed or scrubbed with a stiff brush and flushed with fresh water to remove any remaining solutes and contaminates. Do not wash with solvents unless the contaminant is not water soluble. Allow the area to completely dry out. Employ fans, heaters or vacuum bags if necessary.
Apply the putty mixture to the damaged area to a thickness of about $\frac{1}{16}$". Inspect the repair in accordance with Quality Assurance requirements. Wet-sand and buff gel coated surface or sand and paint when matching a painted finish		After the gel coat has cured remove the PVA and sand the gel coat smooth with 100-120 grit sandpaper, feathering into the surrounding surface. Vacuum the dust and wipe down the repair with acetone. Apply primer and paint in accordance with the manufacturer's specifications.	Use kraft paper and masking tape to mask around the area being repaired Prepare a priming coat of gel coat resin following manufacturers specifications. Coat the void with resin, working the resin into any exposed fibers. Complete the repair consistent as per appropriate procedures defined at left.

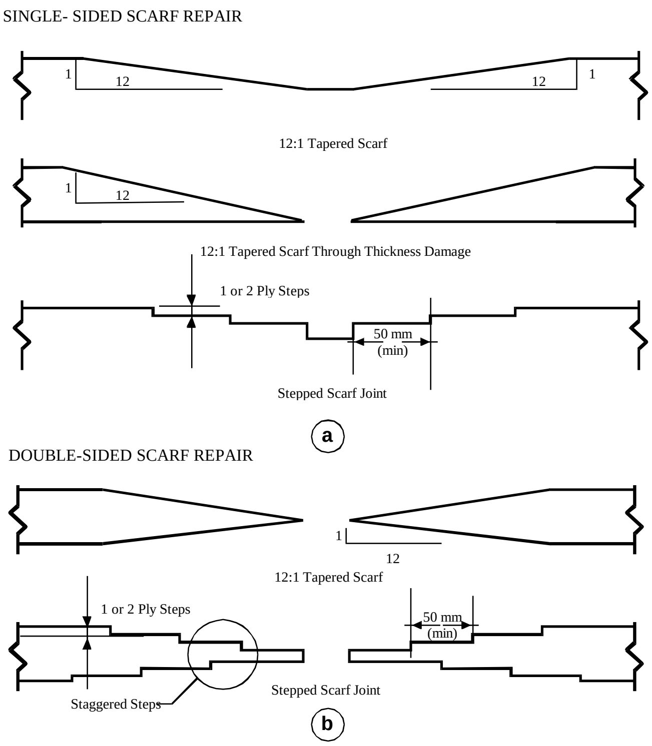


Figure 5-56 Scarf Joint Preparation

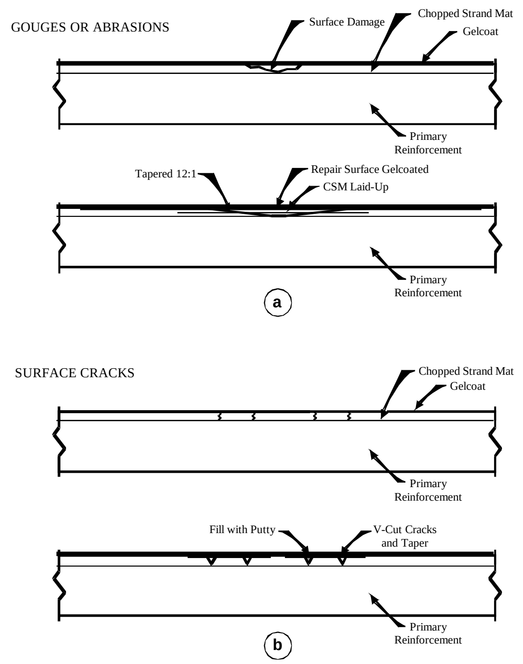


Figure 5-58 Surface Damage Repair

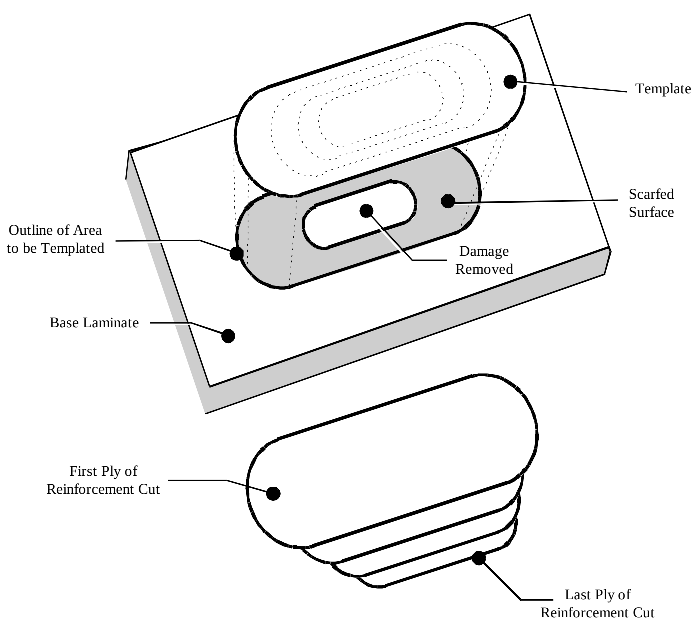


Figure 5-57 Templating Reinforcement

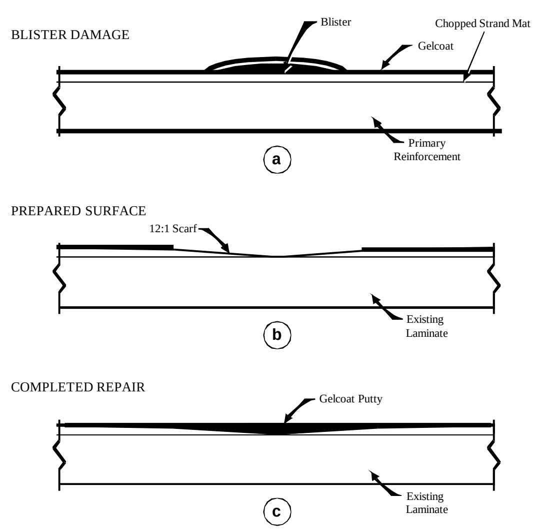


Figure 5-59 Blister Damage Repair

Table 5-8 Structural Damage

Partially-Through Thickness Damage	Through Thickness Damage	Access to One Side	Tabbed Joint Connections
Figure 5-60 depicts partial through-thickness damage.	Figure 5-61 depicts through-thickness damage. The repair approach selected for through thickness damage will depend on the thickness of the laminate and whether or not both sides of the damaged structure are accessible.	The procedures for repairing through thickness damage from one side due to access limitations are similar to those used when making a repair with a single sided scarf; the difference being the backing plate will become part of the repair patch. In this case the backing plate should be GRP, as illustrated in Figure 5-66.	Decks and bulkheads are joined to one another and to the shell by tabbed joint connections. Damage to these connections can be in the form of debunks or delaminations, resin whitening at the root of the tabbed joint, and cracks. Root whitening by itself need not be repaired unless combined with other types of damage such as debunks or cracks. Figure 4-40a illustrates tabbed joint damage.
Clear away any loose or fragmented GRP. Remove the paint and primer in the vicinity of the damage using a 60 grit disk. Vacuum the dust and wipe the area with acetone. Verify the extent of the damage. This can be done visually, with a tapping hammer or by employing non-destructive testing methods such as ultrasonic testing. Remark the damaged area if necessary	When selecting a scarf detail. for laminates thicker than 1/4" (6 mm), and when both sides are accessible, a double-side scarf repair is recommended for maximum strength. Remove equipment and outfitting items which may interfere with the repair. Number the items removed and sketch their position so that they can be put back in their proper location.		For debunks, delaminations, and cracks, the damaged laminate will have to be removed and the connection rebuilt to restore structural integrity of the joint. Resin injection under a debonded stepped angle connection is not an acceptable permanent repair approach. Once the damaged tabbed joint is removed, the base laminate can be assessed for damage.
Grind away the damaged laminate using a 16 - 40 grit disk. Periodically check the soundness of the laminate while grinding. If the damage depth can be determined, a circular saw or grinding wheel set to the depth of the damage can be used to make a series of close cuts into the damaged laminate. The damaged laminate can then be undercut and removed with a grinder or hammer and chisel. If the damage extends through the laminate, follow those procedures and revise the repair plan as necessary.	Clear away any loose or fragmented GRP. Remove the paint and primer in the vicinity of the damage using a 60 grit disk. Vacuum the dust and wipe the area with acetone. Verify the extent of the damage. This can be done visually, with a tapping hammer or by employing non-destructive testing methods such as ultrasonic testing. Remark the damaged area if necessary.	Remove the damaged laminate and prepare the scarf joint following the procedures in the preceding section.	For a debonded tabbed joint where its tows have separated, wood wedges can be driven under the tows of the tabbed joint to pry it loose from the joined structure.
If the damage area is contaminated (fresh water, salt water, or tank fluids), either remove the contaminated GRP or clean and dry the GRP following the guidelines in this section. After removing the damaged laminate, mark the perimeter of the scarf zone and select an appropriate scarf method.	At this point, various techniques can be used to remove the damaged laminate and prepare the required scarf joint. One approach for a double sided scarf repair is to completely cut away the damaged laminate using a circular saw, Sawz-all or die grinder with a grit edge cutting wheel. Both sides of the laminate are scarfed with the transition plane formed at the midplane of the laminate. A backing plate is then shaped to the contour of the scarfed surface as illustrated in Figure 5-62.	Develop a template for the backing plate using kraft paper, 3" (75 mm) wider all around than the opening in the laminate. Cut 2 or 3 plies of CSM or WR and laminate them on a waxed table. The backing plate should be stiff enough to support lamination of the repair patch.	After removing the damaged tabbed joint, inspect the surrounding laminate. Construction tolerances are such that there may be gaps between the joining components, such as between a bulkhead and shell. During construction, gaps are sometimes filled with a resin-glass mixture. Loose filler should be extracted and replaced. Formulate a resin putty consisting of milled fibers and fill the gaps as necessary.
Start from the damaged area and grind back to the scarf perimeter using a 16 - 40 grit disk or rough cut the scarf, then fair it out with a grinder. The scarf must be smooth and even. There should not be any sharp edges or ridges. Corners should be rounded, with a minimum radius of 1" (24 mm). A wooden template shaped to the desired slope can be used as a guide in forming the scarf. Figure 5-56b illustrates a tapered scarf.	A second option is to form a scarf on the near side of the laminate to half its depth. A backing plate is then fit up to the backside such that it is flush with the scarf. After laminating the patch on the near side, the far side of the laminate is scarfed. This option is illustrated in Figure 5-63.	Trim the backing plate as necessary to enable it to pass through the hole. Insert a wire or some other mechanical device as shown in Figure 5-66. This will be used to temporarily hold the backing plate in place.	
	A third option is to remove approximately 50% of the thickness of the damage laminate, using the remaining thickness, if intact, as a pseudo backing plate. The damage can then be worked as a partial through thickness. The remaining damage is then repaired following a similar approach. See Figure 5-64.	Mix enough resin putty to coat the edges of the backing plate. The resin putty will hold the plate in place once cured.	
	Doublers should be considered on the non-molded side to reinforce the repair. The first doubler ply should overlap the joint by 6" (150 mm) and each successive ply should overlap by an additional 1" (25 mm).	Insert the plate through the hole and secure it in place. Fill any gaps with resin putty. After the putty cures, clip the wire and prepare the surface for laminating	A compound scarf joint is required such that the reinforcement can be stepped in the lengthwise direction away from the corner and parallel to the connection, see Figure 4-40b and 4-40c.

Continued on next page

Partially-Through Thickness Damage	Through Thickness Damage	Access to One Side	Tabbed Joint Connections
Remove at least 2" (50 mm) of paint and primer from the edges of the scarf perimeter using a 60 grit disk, being careful not to grind into the gel coat if present. If additional plies are to be placed over top of the repair as additional reinforcement, grind back the gel coat a sufficient distance to account for the overlapping plies.	Single sided scarf joints are applicable for laminates ¼" (6 mm) or less, as illustrated in Figure 5-65. If the damage area is contaminated (fresh water, salt water, or tank fluids), either remove the contaminated GRP or clean and dry the GRP.	Sand the surface of the backing plate with a 60 grit disk to provide a clean smooth surface. Vacuum the dust and wipe down the area with acetone.	Laminate and finish repair as per procedures outlined in Tables 5-7 and 5-8
Thoroughly vacuum the dust and grit and wipe the area down with acetone.	After removing the damaged laminate, mark the perimeter of the scarf zone. The extent of the scarf will depend on the type of scarf joint selected and the depth of the laminate	Laminate and finish repair as per procedures outlined in Tables 5-7 and 5-8.	
Once the area has been prepared for lamination, perform a final inspection verifying that the existing laminate is sound, the scarf is properly formed, all edges are rounded and the area is clean and dry.	Start from the damaged area and grind back to the scarf perimeter using a 16-40 grit disk or rough cut the scarf using a circular saw or die grinder forming a series of close tapered cuts. The GRP can then be undercut and removed with the die grinder or hammer and chisel. A gel coat peeler is also effective in removing damaged laminate. The scarf joint is then shaped and finished off with a 60 grit disk. The scarf must be smooth and even and have a relatively fine terminus. There should not be any sharp edges. Corners should be rounded with a minimum radius of 1" (24 mm). A wooden template shaped to the desired slope may be helpful in forming the scarf.		
Apply release wax around the perimeter of the repair area to protect it from resin and gel coat runs and drips. In addition, mask the area with Kraft paper and masking tape. Mask just beyond the edge of the paint.	Remove at least 2" (50 mm) of paint and primer from the edges of the scarf line using a 60 grit disk, being careful not to grind into the gel coat if present. If additional plies are to be placed over top of the repair as additional reinforcement, grind back the gel coat to account for the overlapping plies.		
Estimate the amount of materials, i.e., fiberglass and resin, based on the repair area.			
Develop a template for cutting the glass as per Figure 5-57 and cut the reinforcement to size. Organize the reinforcement stacked according to the lamination sequence.	Thoroughly vacuum the fiberglass dust and grit and wipe the area with acetone.		
Formulate the resin and laminate the repair following the laminating guidelines in Tables 5-7 and 5-8.	Once the area has been prepared for lamination, perform a final inspection verifying that the existing laminate is sound, the scarf is properly formed, all edges are rounded and the area is clean and dry.		
Inspect the repair in accordance with the Quality Assurance Requirements.	Apply wax around the outside perimeter of the repair area to protect it from resin and gel coat runs and drips. In addition, mask the area with Kraft paper and masking tape. Mask just beyond the edge of the paint.		
Apply finish to match the base structure.			
	Fabricate a backing plate or mold such that it extends several inches beyond the inner edge of the scarf. The backing plate can be formed out of cardboard, polyurethane foam, fiberglass sheet, thin aluminum or sheet metal, plywood, Formica, etc.. It should be stiff enough to resist pressure from consolidating the reinforcement, and it should conform to the surface contour. The backing plate or mold should be covered with mold release wax and aluminum foil, release film or PVA (at least 3 coats). If PVA is used make sure it has completely dried before proceeding to the next step.		
	Securely attach the backing plate to the laminate using an adhesive, resin putty, clamps or self tapping screws. The backing plate should fit tightly to the edge of the scarf to prevent resin seepage. Where part of the damaged laminate is left in place as backing, the damaged portion should be waxed and covered with aluminum foil or coated with PVA to prevent bonding to the in-situ damage. Take care not to get mold release on the scarfed surface being laminated.		
	Laminate and finish repair as per procedures outlined in Tables 5-7 and 5-8.		

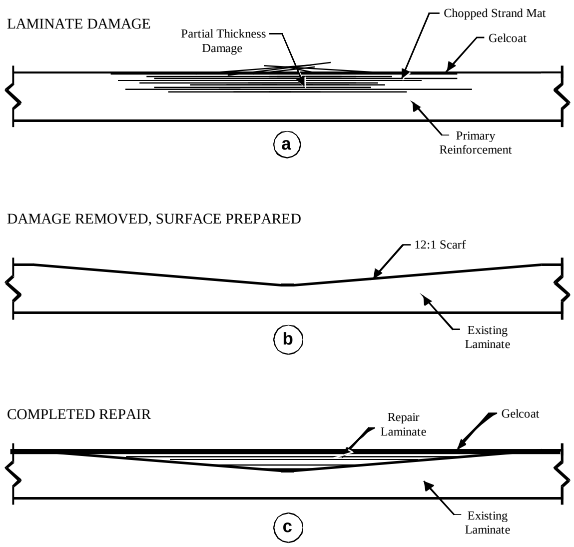


Figure 5-60 Partial Through Thickness Damage Repair

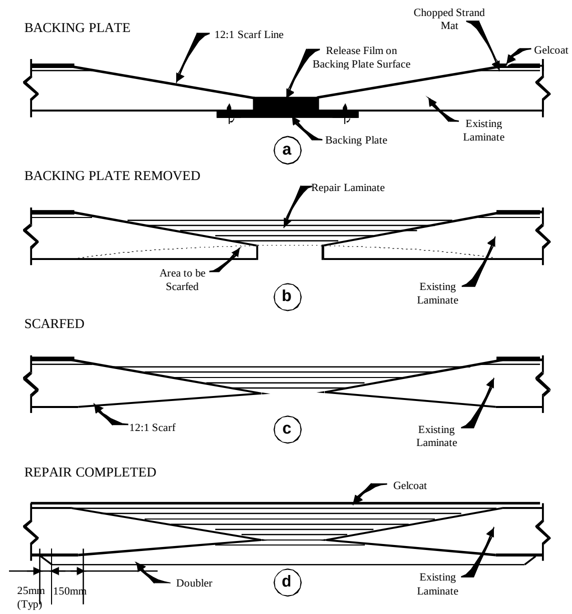


Figure 5-63 Backing Plate Installation - One Sided Scarf Repair

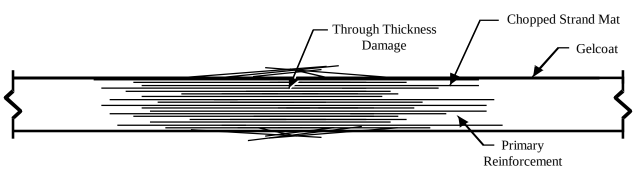


Figure 5-61 Through Thickness Damage

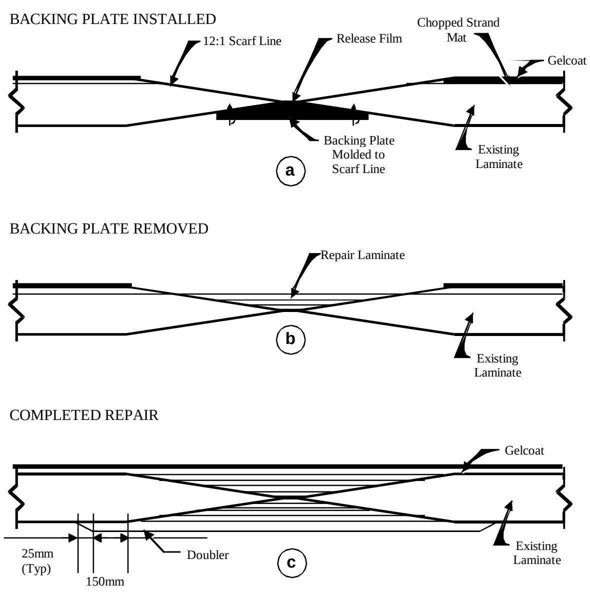


Figure 5-62 Backing Plate Installation - Double-Sided Scarf Repair

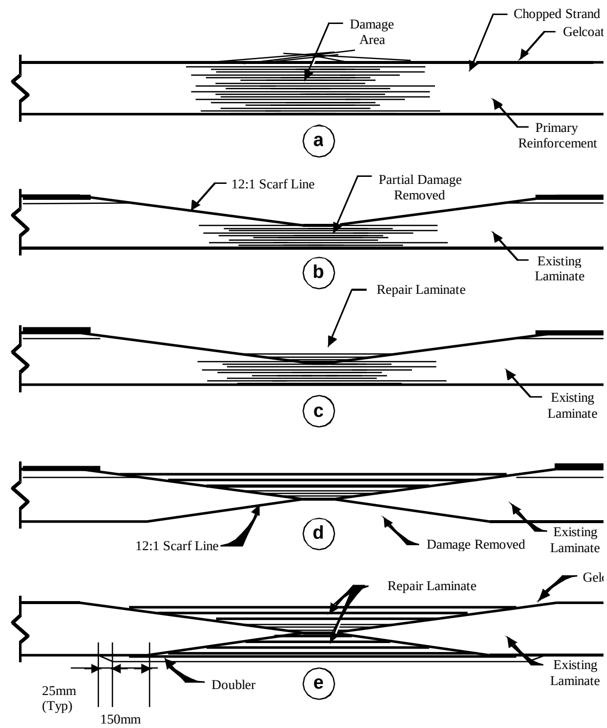


Figure 5-64 Repair Using Damaged Section as Backing Plate

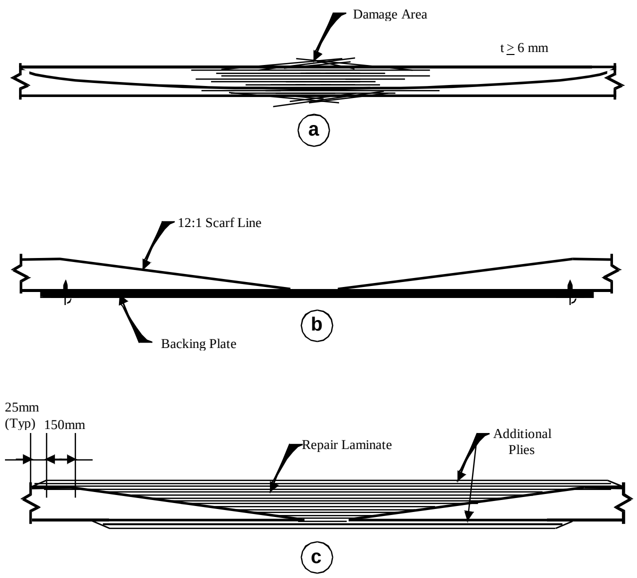


Figure 5-65 Single Sided Scarf Repair

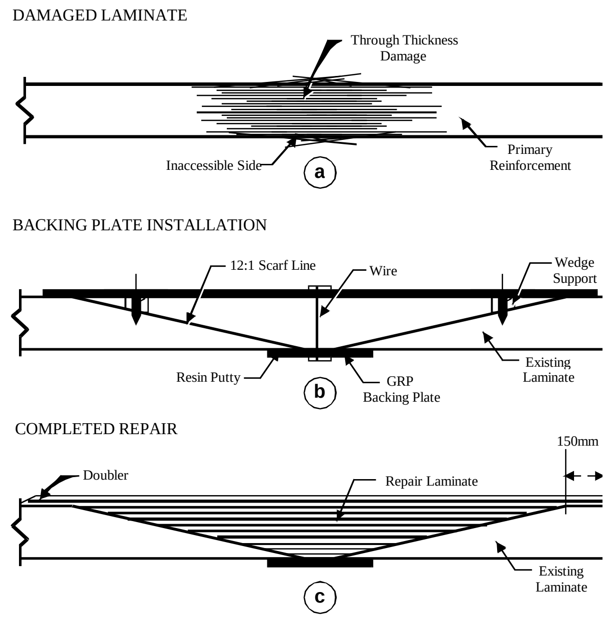


Figure 5-66 Backing Plate Installation - Access from One Side

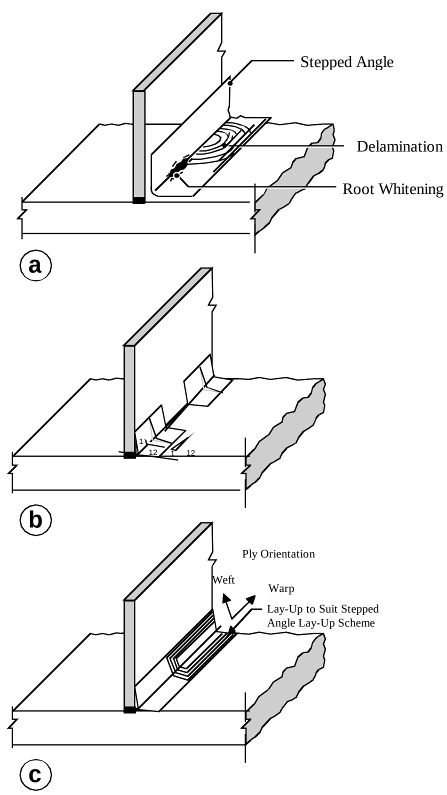


Figure 5-67 Tabbed Joint Damage Repair

Major Damage in Sandwich Construction

Determining the extent of damage with sandwich construction is a bit more difficult because debonding may extend far beyond the area of obvious visual damage. The cut back area should be increasingly larger proceeding from the outer to the inner skin as shown in Figure 5-68. Repair to the skins is generally similar to that for single-skin construction. The new core will necessarily be thinner than the existing one to accommodate the additional repair laminate thickness. Extreme care must be exercised to insure that the core is properly bonded to both skins and the gap between new and old core is filled.

Core Debonding

Repairing large sections of laminate where the core has separated from the skin can be costly and will generally result in a structure that is inferior to the original design, both from a strength and weight standpoint. Pilot holes must be drilled throughout the structure in the areas suspected to be debonded. These holes will also serve as ports for evacuation of any moisture and injection of resin, which can restore the mechanical aspects of the core bond to a certain degree. In most instances, the core never was fully bonded to the skins as a result of manufacturing deficiencies.

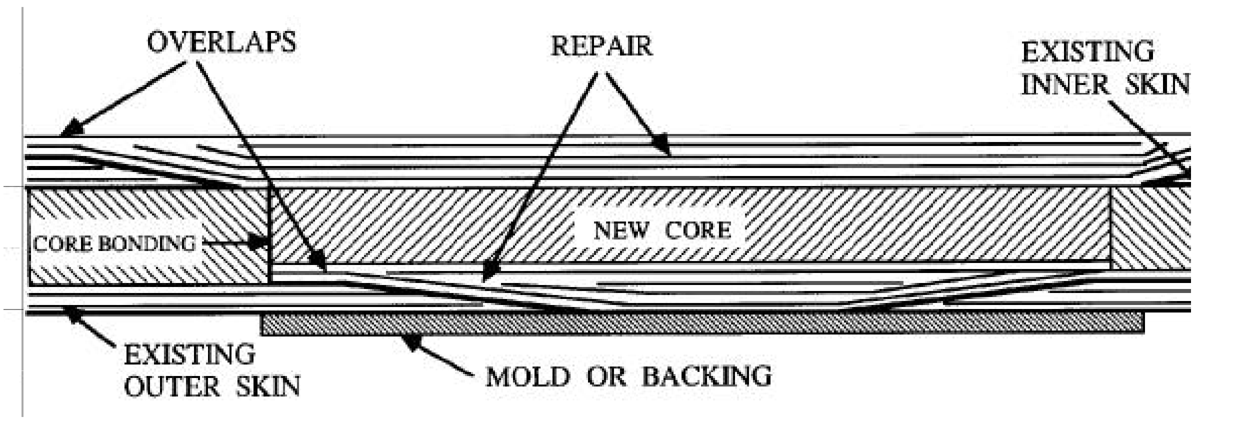


Figure 5-68 Technique for Repairing Damage to Sandwich Construction [USCG NVIC No. 8-87]

Small Non-Penetrating Holes

If the structural integrity of a laminate has not been compromised, a repair can be accomplished using a “structural” putty. This mixture usually consists of resin or a gel coat formulation mixed with milled fibers or other randomly oriented filler that contributes to the mixture's strength properties.

There are many "off-the-shelf" pastes, putties and fillers formulated for marine uses that are suitable for surface repairs. One such product is Poly-Fair R26. Note that auto body filler should not be used since it is more susceptible to moisture absorption. Gel coat putty can also be formulated on site by thickening the gel coat with Cab-O-Sil. Milled fibers should not be used with gel coat since the fibers are more susceptible to moisture absorption. Do not use epoxy putty where gel coat will be applied. The gel coat will not bond well to epoxy.

Thin scratches and gouges can be removed using a drill with a burr or sanding sleeve or a die grinder, forming a V-groove along the length of the flaw. Feather the edges of the "V" to the existing laminate using a 100 grit disk to provide a bonding surface for gel coat putty or a suitable filler, see Figure 5-58b. Remove the paint from the edges of the ground out area using a 60 grit disk, being careful not to grind away the gel coat.

For minor surface damage, filler is only required to thicken the mixture for workability. The following general procedure [4-36] can be followed:

- Clean surface with acetone to remove all wax, dirt and grease;
- Remove the damaged material by sanding or with a putty knife or razor blade. Wipe clean with acetone, being careful not to saturate the area;
- Formulate the putty mixture using about 1% MEKP catalyst;
- Apply the putty mixture to the damaged area to a thickness of about $\frac{1}{16}$";
- If a gel coat mixture is used, a piece of cellophane should be placed over the gel coat and spread out with a razor's edge. After about 30 minutes, the cellophane can be removed; then
- Wet-sand and buff gel coated surface or sand and paint when matching a painted finish.

Blisters

The technique used to repair a blistered hull depends on the extent of the problem. Where blisters are few and spaced far apart, they can be repaired on an individual basis. If areas of the hull have a cluster of blisters, gel coat should be removed from the vicinity surrounding the problem. In the case where the entire bottom is severely blistered, gel coat removal and possibly some laminate over the entire surface is recommended. The following overview and procedures in Table 5-7 should be followed:

Gel Coat Removal: Sand blasting is not recommended because it shatters the underlying laminate, thus weakening the structure. Also, the gel coat is harder than the laminate, which has the effect of quickly eroding the laminate once the gel coat is removed. Grinding or sanding until the laminate has a "clear" quality is the preferred approach.

Laminate Preparation: It is essential that the laminate is clean. If the blister cannot be completely removed, the area should be thoroughly washed with water and treated with a water soluble silane wash. A final wash to remove excess silane is recommended. The laminate is then required to be thoroughly dried. Vacuum bagging is an excellent way to accomplish this. In lieu of this, moderate heat application and fans can work.

Resin Coating: The final critical element of the repair procedure is the selection of a resin to seal the exposed laminate and create a barrier layer. As illustrated in the Blisters section (page 197), vinyl ester resins are superior for this application and are chemically compatible with polyester laminates, which to date are the only materials to exhibit blistering problems. Epoxy resin in itself can provide the best barrier performance, but the adhesion to other materials will not be as good. Epoxy repair might be most appropriate for isolated blisters, where the increased cost can be justified.

Quality Assurance

Unlike a structure fabricated from metal plate, a composite hull achieves its form entirely at the time of fabrication. As a result, the overall integrity of an FRP marine structure is very dependent on a successful Quality Assurance Program (QAP) implemented by the builder. This is especially true when advanced, high-performance craft are constructed to scantlings that incorporate lower safety factors. In the past, the industry has benefited from the process control leeway afforded by structures considered to be "overbuilt" by today's standards. Increased material, labor and fuel costs have made a comprehensive QAP seem like an economically attractive way of producing more efficient marine structures.

The basic elements of a QAP include:

- Inspection and testing of raw materials including reinforcements, resins and cores;
- In-process inspection of manufacturing and fabrication processes; and
- Destructive and non-destructive evaluation of completed composite structures.

Destructive testing methods include laminate testing (see page 111). Each builder must develop a QAP consistent with the product and facility. Figure 5-69 shows the interaction of various elements of a QAP. The flowing elements should be considered by management when evaluating alternative QAPs: [5-31]

- Program engineered to the structure;
- Sufficient organization to control labor intensive nature of FRP construction;
- Provide for training of production personnel;
- Timely testing during production to monitor critical steps;
- Continuous production process monitoring with recordkeeping;
- Simple, easily implemented program consistent with the product;
- Emphasis on material screening and in-process monitoring as laminates are produced on site;
- The three sequences of a QAP, pre, during and post construction, should be allocated in a manner consistent with design and production philosophy;
- Specifications and standards for composite materials must be tailored to the material used and the application; and
- The balance between cost, schedule and quality should consider the design and performance requirements of the product.

Table 5-9 lists some questions that engineering personnel must evaluate when considering the design and implementation of a QAP. [5-31]

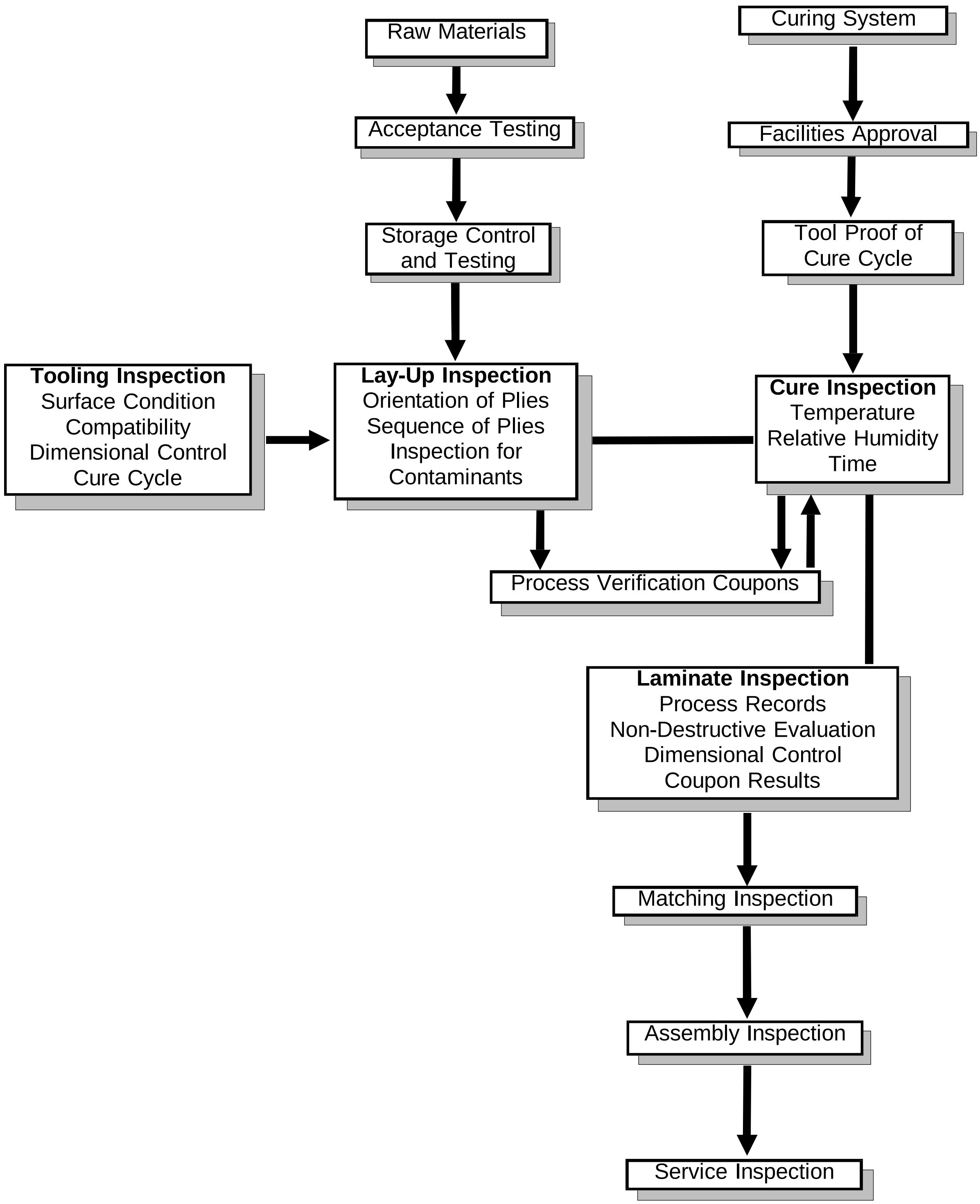


Figure 5-69 Inspection Requirements for Composite Materials [U.S. Air Force, *Advanced Composite Design*]

Table 5-9 Engineering Considerations Relevant to an FRP Quality Assurance Program [Thomas and Cable, *Quality Assessment of Glass Reinforced Plastic Ship Hulls in Naval Applications*]

Engineering Considerations	Variables
Design Characteristics	Longitudinal bending, panel deflection, cost, weight, damage tolerance
Material Design Parameters	Interlaminar shear strength, compressive strength, shear strength, tensile strength, impact strength, stiffness, material cost, material production cost, material structural weight, material maintenance requirements
Stress Critical Areas	Keel area, bow, shell below waterline, superstructure, load points
Important Defects	Delaminations, voids, inclusions, uncured resin, improper overall glass to resin ratio, local omission of layers of reinforcement, discoloration, crazing, blisters, print-through, resin starved or rich areas, wrinkles, reinforcement discontinuities, improper thickness, foreign object damage, construction and assembly defects
Defect Prevention	Proper supervision, improving the production method, material screening, training of personnel, incorporation of automation to eliminate the human interface in labor intensive production processes
Defect Detection	Evaluation of sample plugs from the structure, testing of built-in test tabs, testing of cutouts for hatches and ports, nondestructive testing of laminated structure
Defect Correction	Permanent repair, replacement, temporary repair
Defect Evaluation	Comparison with various standards based on: defect location, severity, overall impact on structural performance
Effort Allocation	Pre-construction, construction, post-construction

Materials

Quality assurance of raw materials can consist of qualification inspections or quality conformance inspections. Qualification inspections serve as a method for determining the suitability of particular materials for an application prior to production. Quality conformance inspections are the day-to-day checks of incoming raw material designed to insure that the material conforms with minimum standards. These standards will vary, depending on the type of material in question.

Reinforcement Material

Inspection of reinforcement materials consists of visual inspection of fabric rolls, tests on fabric specimens and tests on laminated samples. Effort should concentrate on visual inspection as it represents the most cost effective way an average boat builder can ensure raw material conformance. Exact inspection requirements will vary depending upon the type of material (E- and S-Glass, Kevlar®, carbon fiber, etc.) and construction (mat, gun-roving, woven roving, knit, unidirectional, prepreg, etc.). As a general guideline, the following inspection rejection parameters should be applied to rolled goods: [5-32]

- Uncleanliness (dirt, grease, stains, spots, etc.);
- Objectionable odor (any odor other than finishing compounds);
- Color not characteristic of the finish or not uniform;
- Fabric brittle (fibers break when flexed) or fused;
- Uneven weaving or knitting throughout clearly visible; and
- Width outside of specified tolerance.

The builder will also want to make sure that rolls are the length specified and do not contain an excessive number of single pieces. As the material is being rolled out for cutting or use, the following defects should be noted and compared to established rejection criteria:

- Fiber ply misalignment;
- Creases or wrinkles embedded;
- Any knots;
- Any hole, cut or tear;
- Any spot, stain or streak clearly visible;
- Any brittle or fused area;
- Any smashed fibers or fiber bundles;
- Any broken or missing ends or yarns;
- Any thickness variation that is clearly visible;
- Foreign matter adhering to the surface;
- Uneven finish; and
- Damaged stitching or knitted threads.

As part of a builder's overall QAP, lot or batch numbers of all reinforcements should be recorded and correlated with the specific application. The following information should accompany all incoming reinforcement material and be recorded:

- Manufacturer;
- Material identification;
- Vendor or supplier;
- Lot or batch number;
- Date of manufacture;
- Fabric weight and width;
- Type or style of weave; and
- Chemical finish.

The handling and storage of reinforcement material should conform with the manufacturer's recommendations. Material can easily be damaged by rough handling or exposure to water, organic solvents or other liquids. Ideally, reinforcement material should be stored under controlled temperature and relative humidity conditions, as some are slightly hydroscopic. Usually room temperature conditions with adequate protection from rain water is sufficient for fiberglass products. Advanced materials and especially prepregs will have specific handling instructions that must be followed. If the ends of reinforcement rolls have masking tape to prevent fraying, all the adhesive must be thoroughly removed prior to lamination.

Resin

Laminating resin does not reveal much upon visual inspection. Therefore, certain tests of the material in a catalyzed and uncatalyzed state must be performed. The following tests can be performed on uncatalyzed resin:

Specific Gravity - The specific gravity of resin is determined by precisely weighing a known volume of liquid.

Viscosity - The viscosity of uncatalyzed resin is determined by using a calibrated instrument such as a MacMichael or Brookfield viscometer, like the one shown in Figure 5-70.

Acid Number - The acid number of a polyester or vinyl ester resin is an indictor of the amount of excess glycol of the resin. It is defined as the number of milligrams of potassium hydroxide required to neutralize one gram of polyester. It is determined by titrating a suitable sample of material as a solution in neutral acetone with 0.1 normal potassium hydroxide using phenolphthalein as an indicator. Most builders will instead rely on the gel test of catalyzed resin to determine reactivity.

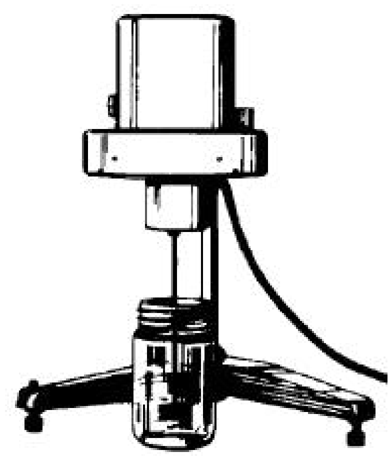


Figure 5-70 Brookfield Model LVF Viscometer and Spindles [Cook, *Polycor Polyester Gel Coats and Resins*]

The testing of catalyzed resin using the following procedures will provide more information, as the tests also reflect the specific catalysts and ambient temperature conditions of the builder's shop.

Gel Time - The gel time of a non-promoted resin is an indicator of the resin's ability to polymerize and harden and the working time available to the manufacturer. The Society of the Plastics Industry and ASTM D-2471 specify alternative but similar methods for determining gel time. Both involve the placement of a fixed amount of catalyzed resin in a elevated temperature water bath. Gel time is measured as the time required for the resin to rise from 150°F to 190°F with temperature measurements made via an embedded thermocouple.

An alternative procedure that is commonly used involves a cup gel timer. Catalyzed resin is placed in a cup and a motorized spindle is activated with a timer. As the resin cures, the spindle slows and eventually stalls the moter at a given torque. Gel time is then read off of the unit's timer device.

Peak Exotherm - The peak exotherm of a catalyzed resin system is an indicator of the heat generation potential of the resin during polymerization, which involves exothermic chemical reactions. It is desirable to minimize the peak exotherm to reduce the heat build-up in thick laminates. The peak exotherm is usually determined by fabricating a sample laminate and recording the temperature rise and time to peak. ASTM D-2471 provides a detailed procedure for accomplishing this.

Barcol Hardness - The Barcol hardness of a cured resin sample is measured with a calibrated Barcol impressor, as shown in Figure 5-71. This test (ASTM D 2583-81) will indicate the degree of hardness achieved during cure as well as the degree of curing during fabrication. Manufacturers will typically specify a Barcol hardness value for a particular resin.

Figure 5-71 Barcol Impressor (Model 934 or 935 for readings over 75) [Cook, *Polycor Polyester Gel Coats and Resins]*

Specific Gravity - Measurement of specific gravity of cured, unfilled resin system involves the weighing of known volume of cured resin.

The following information should accompany all incoming shipments of resin and be recorded by the manufacturer for future reference:

- Product name or code number and chemical type;
- Limiting values for mechanical and physical properties;
- Storage and handling instructions;
- Maximum usable storage life and storage conditions;
- Recommended catalysts, mixing procedure; finishes to use in reinforcements; curing time and conditions; and
- Safety information.

The storage and handling of resin is accomplished either with 55 gallon drums or via specially designed bulk storage tanks. Table 5-10 lists some precautions that should be observed for drum and bulk storage.

Table 5-10 Precautions for Storage and Handling of Resin
[SNAME, *Guide for Quality Assured Fiberglass Reinforced Plastic Structures*]

Drum Storage	Bulk Storage
Date drum upon receipt and store using first-in first-out system to assure stock rotation	Use a strainer to prevent impurities from either the tank truck or to delivery lines
Do not store material more than three months (or per manufacturer's recommendation)	Install a vacuum pressure relief valve to allow air to flow during tank filling and resin usage
Keep drums out of direct sunlight, using covers if outdoors, to prevent water contamination	Use a manhole or conical tank bottom to permit periodic cleanout
Store drums in well ventilated area between 32°F and 77°F	Phenolic and epoxy tank liners prevent the attack of tank metal by stored resin
If drums are stored at a temperature substantially different from laminating area, resin temperature must be brought to the temperature of the laminating area, which usually requires a couple of days	A pump should provide for both the delivery through the lines and the circulation of resin to prevent sedimentation, which can also be controlled with a blade or propeller type stirring device
Keep drums sealed until just prior to use	Electrically ground tank to filling truck
Just prior to insertion of a spigot or pump, make sure that the top of the drum is clean to reduce the risk of contamination	Throttling valves are used to control resin flow rates and level indicators are useful for showing the amount of material on hand

Core Material

In general, core material should be visually examined upon receipt to determine size, uniformity, workmanship and correct identification. Core material can be tested to determine tensile, compressive and shear strength and moduli using appropriate ASTM methods. Density and water absorption, as a minimum, should be tested. Manufacturers will supply storage requirements specific to their product. All core materials should be handled and stored in such a way as to eliminate the potential for contact with water and dirt. This is critical during fabrication as well as storage. Perspiration from workers is a major contamination problem that seriously effects the quality of surface bonds.

In-Process Quality Control

In order to consistently produce a quality laminated product, the fabricator must have some control over the laminating environment. Some guidelines proposed by ABS [5-33] include:

- Premises are to be fully enclosed, dry, clean, shaded from the sun, and adequately ventilated and lighted.;
- Temperature is to be maintained adequately constant between 60°F and 90°F. The humidity is to be kept adequately constant to prevent condensation and is not to exceed 80%. Where spray-up is taking place, the humidity is not to be less than 40%.; and
- Scaffolding is to be provided where necessary so that all laminating work can be carried out without standing on cores or on laminated surfaces.

An in-process quality control program must be individually tailored to the project and personnel involved. Smaller jobs with highly trained laminators may proceed flawlessly with little oversight and controls. Big jobs that utilize more material and a large work force typical need more built-in controls to ensure that a quality laminate is constructed. Selection of materials also plays a critical role in the amount of in-process inspection required. Figure 5-72 gives an indication of some techniques used by the boat building industry. The following topics should be addressed in a quality control program:

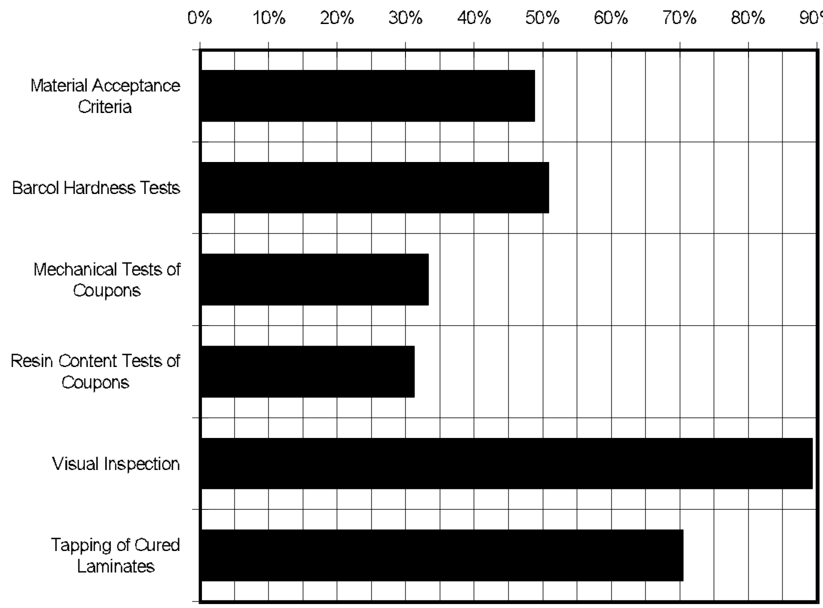


Figure 5-72 Marine Industry Quality Control Efforts [EGA Survey]

- Inspect mold prior to applying releasing agent and gel coat;
- Check gel coat thickness, uniformity of application and perform cure check prior to laminating;
- Check resin formulation and mixing; check and record amounts of base resin, catalysts, hardeners, accelerators, additives and fillers;
- Check that reinforcements are uniformly impregnated and well wet-out and that lay-up is in accordance with specifications;
- Check and record fiber/resin ratio;
- Check that curing is occurring as specified with immediate remedial action if improper curing or blistering is noted;
- Complete overall visual inspection of completed lay-up for defects listed in Table 5-12 that can be corrected before release from the mold; and
- Check and record Barcol hardness of cured part prior to release from mold.

Finished laminates should be tested to guarantee minimum physical properties. This can be done on cut-outs, run-off tabs or on test panels fabricated simultaneously with the hull on a surface that is 45° to the horizontal. Burn-out or acid tests are used to determine the fiber/resin ratio (see page 115). Thickness, which should not vary more than 15%, can also be checked from these specimens. With vessels in production, ABS required the following testing schedule when their services covered boats under 80 feet:

Table 5-11 Proposed Test Schedule for ABS Inspected Vessels [ABS, *Proposed Guide for Building and Classing High-Speed and Displacement Motor Yachts*]

Vessel Length (feet)	Frequency of Testing
Under 30	Every 12th vessel
30 to 40	Every 10th vessel
40 to 50	Every 8th vessel
50 to 60	Every 6th vessel
60 to 70	Every 4th vessel
70 to 80	Every other vessel
80 and over	Every vessel

Table 5-12 Defects Present in Laminated Structures [SNAME, *Guide for Quality Assured Fiberglass Reinforced Plastic Structures]*

Defect Description	Probable Cause
Air Bubble or Voids - May be small and non-connected or large and interconnected	Air entrapment in the resin mix, insufficient resin or poor wetting, styrene boil-off from excessive exotherm, insufficient working of the plies or porous molds
Delaminations - This is the separation of individual layers in a laminate and is probably the most structurally damaging type of defect	Contaminated reinforcement, insufficient pressure during wet-out, failure to clean surfaces during multistage lay-ups, forceful removal of a part from a mold, excessive drilling pressure, damage from sharp impacts, forcing a laminate into place during assembly or excessive exotherm and shrinkage in heavy sections
Crazing - Minute flaws or cracks in a resin	Excessive stresses in the laminate occurring during cure or by stressing the laminate
Warping or Excessive Shrinkage - Visible change in size or shape	Defective mold construction, change in mold shape during exotherm, temperature differentials or heat contractions causing uneven curing, removal from mold before sufficient cure, excess styrene, cure temperature too high, cure cycle too fast or extreme changes in part cross sectional area
Washing - Displacement of fibers by resin flow during wet-out and wiping in the lay-up	Resin formulation too viscous, loosely woven or defective reinforcements, wet-out procedure too rapid or excessive force used during squeegeeing
Resin Rich - Area of high resin content	Poor resin distribution or imperfections such as wrinkling of the reinforcement
Resin Starved - Area of low resin content	Poor resin distribution, insufficient resin, poor reinforcement finish or too high of a resin viscosity
Surface Defects - Flaws that do not go beyond outer ply	Porosity, roughness, pitting, alligatoring, orange peel, blistering, wrinkles, machining areas or protruding fibers
Tackiness or Undercure - Indicated by low Barcol reading or excessive styrene odor	Low concentration of catalyst or accelerators, failure to mix the resin properly, excessive amounts of styrene or use of deteriorated resins or catalysts

Rules and Regulations

The U.S. Coast Guard is statutorily charged with administering maritime safety on behalf of the people of the United States. In carrying out this function, the Coast Guard monitors safety aspects of commercial vessels from design stages throughout the vessel's useful life. Often design standards such as those developed by the American Bureau of Shipping are used. Codes are referenced directly by the U.S. Code of Federal Regulations (CFR) [6-1]. Other countries, such as England, France, Germany, Norway, Italy and Japan have their own standards that are analogous to those developed by ABS. Treatment of FRP materials is handled differently by each country. This section will only describe the U.S. agencies.

U.S. Coast Guard

The Coast Guard operates on both a local and national level to accomplish their mission. On the local level, 42 Marine Safety Offices (MSOs) are located throughout the country. These offices are responsible for inspecting vessels during construction, inspecting existing vessels, licensing personnel and investigating accidents. The Office of Marine Safety, Security and Environment Protection is located in Washington, DC. This office primarily disseminates policy, directs marine safety training, oversees port security and responds to the environmental needs of the country. The Marine Safety Center, also located in Washington, is the office where vessel plans are reviewed. The Coast Guard's technical staff reviews machinery, electrical arrangement, structural and stability plans, calculations and instructions for new construction and conversions for approximately 18,000 vessels a year.

The Coast Guard has authorized ABS for plan review of certain types of vessels. These do not include "Subchapter T" vessels and novel craft. The following section will attempt to describe the various classifications of vessels, as defined in the CFR. Table 6-1 summarizes some of these designations. Structural requirements for each class of vessel will also be highlighted.

Subchapter C - Uninspected Vessels

The CFR regulations that cover uninspected vessels are primarily concerned with safety, rather than structural items. The areas covered include:

- Life preservers and other lifesaving equipment;
- Emergency position indicating radio beacons (fishing vessels);
- Fire extinguishing equipment;
- Backfire flame control;
- Ventilation;
- Cooking, heating and lighting systems; and
- Garbage retention.

Organizations that are cited for reference:

American Boat and Yacht Council
3069 Solomon's Island Road
Edgewater, MD 21037
410-956-1050 / FAX 410-956-2737

National Fire Protection Association (NFPA)
1 Batterymarch Park
Quincy, MA 02269-9101 USA

617-770-3000 / FAX 617-770-0700
http://www.nfpa.org/

Table 6-1 Summary of CFR Vessel Classifications [46 CFR, Part 2.01 - 7(a)]

<table>
<tr><th colspan="2" rowspan="2">Size or Other Limitations</th><th>Subchapter H - Passenger</th><th>Subchapter T - Small Passenger</th><th>Subchapter K - Small Passenger</th><th>Subchapter I Cargo and Miscellaneous</th><th>Subchapter C Uninspected</th></tr>
<tr><td>46 CFR, Parts 70-80</td><td>46 CFR, Part 175</td><td>46 CFR, Part 114</td><td>46 CFR, Parts 90-106</td><td>46 CFR, Parts 24-26</td></tr>
<tr><td rowspan="3">Motor</td><td rowspan="3">Vessels over 15 gross tons except seagoing motor vessels of 300 gross tons and over.Seagoing motor vessels of 300 gross tons and over.</td><td>Vessels over 100 gross tons</td><td>Under 100 gross tons</td><td rowspan="2">All vessels carrying more than 150 passengers or with overnight accommodations for more than 49 passengers</td><td rowspan="3">All vessels carrying freight for hire except those covered by H or T vessels</td><td rowspan="3">All vessels except those covered by H, T, K or I vessels</td></tr>
<tr><td>All other vessels of over 65 feet in length carrying passengers for hire.

All vessels carrying more than 12 and less than 150 passengers on an international voyage, except yachts.</td><td>All vessels not over 65 feet in length which carry more than 6 passengers.</td></tr>
<tr><td colspan="2">All other vessels carrying passengers except yachts.</td><td rowspan="4">Subchapter K' refers to vessels with | 151 passengers or | 61 meters (200 feet)</td></tr>
<tr><td rowspan="3">Sail</td><td rowspan="2">Vessels not over 700 gross tons.</td><td>Vessels over 100 gross tons</td><td>Vessels under 100 gross tons</td><td colspan="2" rowspan="3">Not applicable</td></tr>
<tr><td colspan="2">All vessels carrying more than 6 passengers.</td></tr>
<tr><td>Vessels over 700 gross tons.</td><td colspan="2">All vessels carrying passengers for hire.</td></tr>
</table>

Subchapter H - Passenger Vessels

Part 72 of CFR 46 is titled Construction and Arrangement. Subpart §72.01-15 Structural Standards states:

> In general, compliance with the standards established by ABS will be considered satisfactory evidence of structural efficiency of the vessel. However, in special cases, a detailed analysis of the entire structure or some integral part may be made by the Coast Guard to determine the structural requirements.

Looking at Subpart 72.05 - Structural Fire Protection, under §72.05-10 Type, location and construction of fire control bulkheads and decks, it is noted:

> The hull, structural bulkheads, decks, and deckhouses shall be constructed of steel or other equivalent metal construction of appropriate scantlings.

The section goes on to define different types of bulkheads, based fire performance.

Subchapter I - Cargo and Miscellaneous Vessels

The requirements for "I" vessels is slightly different than for "H". Under Subpart 92.07 - Structural Fire Protection, §92.07-10 Construction states:

> The hull, superstructure, structural bulkheads, decks and deckhouses shall be constructed of steel. Alternately, the Commandant may permit the use of other suitable materials in special cases, having in mind the risk of fire.

Subchapter T - Small Passenger Vessels

§177.300 Structural Design

Except as otherwise noted by this subpart, a vessel must comply with the structural design requirements of one of the standards listed below for the hull material of the vessel.

> (c) Fiber reinforced plastic vessels:
>
> (1) Rules and Regulations for the Classification of Yachts and Small Craft, Lloyd's; or
>
> (2) Rules for building and Classing Reinforced Plastic Vessels, ABS

§177.405 General arrangement and outfitting

> (a) The general construction of the vessel shall be such as to minimize fire hazards insofar as reasonable and practicable. .

§177.410 Structural fire protection.

(a) *Cooking areas.* Vertical or horizontal surfaces within 910 millimeters (3 feet) of cooking appliances must have an American Society for Testing and Materials (ASTM) E-84 "Surface Burning Characteristics of Building Materials" flame spread rating of not more than 75. Curtains, draperies, or free hanging fabrics must not be fitted within 910 millimeters (3 feet) of cooking or heating appliances.

(b) *Fiber reinforced plastic..* When the hull, decks, deckhouse, or superstructure of a vessel is partially or completely constructed of fiber reinforced plastic, including composite construction, the resin used must have an ASTM E-84 flame spread rating of not more than 100.

(c) *Use of general purpose resin* - General purpose resins may be used in lieu of those having an ASTM E 84 flame spread rating of not more than 100 provided that the following additional requirements are met:

(1) Cooking and Heating Appliances - Galleys must be surrounded by "B-15" Class fire boundaries. This may not apply to concession stands that are not considered high fire hazards areas (galleys) as long as they do not contain medium to high heat appliances such as deep fat fryers, flat plate type grilles, and open ranges with heating surfaces exceeding 121°C (250°F). Open flame systems for cooking and heating are not allowed.

(2) *Sources of Ignition* - Electrical equipment and switch boards must be protected from fuel or water sources. Fuel lines and hoses must be located as far as practical from heat sources. Internal combustion engine exhausts, boiler and galley uptakes, and similar sources of ignition must be kept clear of and suitability insulated from any woodwork or other combustible matter. Internal combustion engine dry exhaust systems must be installed in accordance with ABYC Standard P-1.

(3) *Fire Detection and Extinguishing Systems* - Fire detection and extinguishing systems must be installed in compliance with §181.400 through §181.420 of this chapter. Additionally, all fiber reinforced plastic (FRP) vessels constructed with general purpose resins must be fitted with a smoke activated fire detection system of an approved type, installed in accordance with §76.27 in subchapter H of this chapter, in all accommodation spaces, all service spaces, and in isolated spaces such as voids and storage lockers that contain an ignition source such as electric equipment or piping for a dry exhaust system.

(4) *Machinery Space Boundaries* - Boundaries that separate machinery spaces from accommodation spaces, service spaces, and control spaces must be lined with noncombustible panels or insulation approved in accordance with §164.009 in subchapter Q of this chapter, or other standard specified by the Commandant.

(5) *Furnishings* - Furniture and furnishings must comply with §116.423 in subchapter K of this chapter.

(d) *Limitations on the use of general purpose resin.*

(1) *Overnight Accommodations* - Vessels with overnight passenger accommodations must not be constructed with general purpose resin.

(2) *Gasoline Fuel Systems* - Vessels with engines powered by gasoline or other fuels having a flash point of 43.3° C (110° F) or lower must not be constructed with general purpose resin, except for vessels powered by outboard engines with portable fuel tanks stored in an open area aft, if, as determined by the cognizant OCMI, the arrangement does not produce an unreasonable hazard.

(3) *Cargo* - Vessels carrying or intended to carry hazardous combustible or flammable cargo must not be constructed with general purpose resin.

Subchapter K - Small Passenger Vessels

Subpart C - Hull Structure

§116.300 Structural Design provides for steel or aluminum hulls only with alternate design considerations based on engineering principles that show that the vessel structure provides adequate safety and strength. Of major concern to the U.S. Coast Guard would be the added fire threat of a composite hull. The IMO High-Speed Craft Code (see Fire Testing section) may form the basis for an alternative acceptable criteria.

Subpart D - Fire Protection

§116.400 Application.

(a) This subpart applies to:

(1) Vessels carrying more than 150 passengers; or

(2) Vessels with overnight accommodations for more than 49 passengers but not more than 150 passengers.

(b) A vessel with overnight accommodations for more than 150 passengers must comply with §72.05 in subchapter H of this chapter.

§116.405 General arrangement and outfitting.

(a) *Fire hazards to be minimized.* The general construction of the vessel must be such as to minimize fire hazards insofar as it is reasonable and practicable.

(b) *Combustible materials to be limited.* Limited amounts of combustible materials such as wiring insulation, pipe hanger linings, nonmetallic (plastic) pipe, and cable ties are permitted in concealed spaces except as otherwise prohibited by this subpart.

(c) *Combustibles insulated from heated surfaces.* Internal combustion engine exhausts, boiler and galley uptakes, and similar sources of ignition must be kept clear of and suitably insulated from combustible material.

(d) *Separation of machinery and fuel tank spaces from accommodation spaces.* Machinery and fuel tank spaces must be separated from accommodation spaces by boundaries that prevent the passage of vapors.

(e) *Paint and flammable liquid lockers.* Paint and flammable liquid lockers must be constructed of steel or equivalent material, or wholly lined with steel or equivalent material.

(f) *Nonmetallic piping in concealed spaces.* The use of short runs of nonmetallic (plastic) pipe within a concealed spaces in a control space, accommodation space, or service space is permitted in nonvital service only, provided it is not used to carry flammable liquids (including liquors of 80 proof or higher) and:

(1) Has flame spread rating of not more than 20 and a smoke developed rating of not more than 50 when filled with water and tested in accordance with American Society for Testing and Materials (ASTM E 84 "*Test for Surface Burning Characteristics of Building Materials*,") or Underwriters Laboratories (UL) 723 "Test for Surface Burning Characteristics of Building Materials," by an independent laboratory; or

(2) Has a flame spread rating of not more than 20 and a smoke developed rating of not more than 130 when empty and tested in accordance with ASTM E 84 or UL 723 by an independent laboratory

(g) *Vapor barriers***.** Vapor barriers must be provided where insulation of any type is used in spaces where flammable and combustible liquids or vapors are present, such as machinery spaces and paint lockers.

(h) *Interior finishes.* Combustible interior finishes allowed by §116.422 (d) of this part must not extend into hidden spaces, such as behind linings, above ceilings, or between bulkheads.

(i) *Waste Receptacles.* Unless other means are provided to ensure that a potential waste receptacle fire would be limited to the receptacle, waste receptacles must be constructed of noncombustible materials with no openings in the sides or bottom.

(f) *Mattresses*. All mattresses must comply with either:

(1) The U.S. Department of Commerce Standard for Mattress Flammability (FF 4-72.16), 16 CFR Part 1632, Subpart A and not contain polyurethane foam; or

(2) International Maritime Organization Resolution A.688(17) "*Fire Test Procedures For Ignitability of Bedding Components*." Mattresses that are tested to this standard may contain polyurethane foam.

§116.415 Fire control boundaries.

(a) *Type and construction of fire control bulkheads and decks.*

(1) *Major hull structure* - The hull, structural bulkheads, columns and stanchions, superstructures, and deckhouses must be composed of steel or equivalent material, except that where "C'-Class" construction is permitted by Tables 116.415 (b) and (c), bulkheads and decks may be constructed of approved noncombustible materials.

(2) *Bulkheads and decks* - Bulkheads and decks must be classed as "A-60," "A-30," "A-15," "A-0," "B-15," "B-0," "C," or "C'" based on the following:

(i) A-Class bulkheads or decks must be composed of steel or equivalent material, suitably stiffened and made intact with the main structure of the vessel, such as the shell, structural bulkheads, and decks. They must be so constructed that, if subjected to the standard fire test, they are capable of preventing the passage of smoke and flame for one hour. In addition, they must be so insulated with approved structural insulation, bulkhead panels, or deck covering so that, if subjected to the standard fire test for the applicable time period listed below, the average temperature on the unexposed side does not rise more than 139°C (250°F) above the original temperature, nor does the temperature at any one point, including any joint, rise more than 181°C (325°F) above the original temperature:

"A-60 Class"	60 minutes
"A-30 Class"	30 minutes
"A-15 Class"	15 minutes
"A-0 Class"	0 minutes

(ii) Penetrations in "A-Class" fire control boundaries for electrical cables, pipes, trunks, ducts, etc. must be constructed to prevent the passage of flame and smoke for one hour. In addition, the penetration must be designed or insulated so that it will withstand the same temperature rise limits as the boundary penetrated.

(iii) "B-Class bulkheads" and decks must be constructed of noncombustible materials and made intact with the main structure of the vessel, such as shell, structural bulkheads, and decks, except that a B-Class bulkhead need not extend above an approved continuous B-Class ceiling. They must be so constructed that, if subjected to the standard fire test, they are capable of preventing the passage of flame for 30 minutes. In addition, their insulation value must be such that, if subjected to the standard fire test for the applicable time period listed below, the average temperature of the unexposed side does not rise more than 139°C (250°F) above the original temperature, nor does the temperature at any one point, including any joint, rise more than 225° C (405° F) above the original temperature:

"B-15 Class"	15 minutes
"B-0 Class"	0 minutes

(iv) Penetrations in "B-Class" fire control boundaries for electrical cables, pipes, trunks, ducts, etc. must be constructed to prevent the passage of flame for 30 minutes. In addition, the penetration must be designed or insulated so that it will withstand the same temperature rise limits as the boundary penetrated.

(v) "C-Class" bulkheads and decks must be composed of noncombustible materials.

(vi) "C'-Class" bulkheads and decks must be constructed of noncombustible materials and made intact with the main structure of the vessel, such as shell, structural bulkheads, and decks, except that a "C'-Class" bulkhead need not extend above a continuous "B-Class" or "C'-Class" ceiling. "C'-Class" bulkheads must be constructed to prevent the passage of smoke between adjacent areas. Penetrations in "C'-Class" boundaries for electrical cables, pipes, trunks, ducts, etc. must be constructed so as to preserve the smoke-tight integrity of the boundary.

(vii) Any sheathing, furring, or holding pieces incidental to the securing of structural insulation must be an approved noncombustible material.

(b) *Bulkhead requirements*. Bulkheads between various spaces must meet the requirements of Table 116.415(b).

(c) *Deck requirements.* Decks between various spaces must meet the requirements of Table 116.415(c), except that where linings or bulkhead panels are framed away from the shell or structural bulkheads, the deck within the void space so formed need only meet A-0 Class requirements.

(d) *Main vertical zones.*

(1) The hull, superstructure, and deck houses of a vessel, except for a vehicle space on a vehicle ferry, must be subdivided by bulkheads into main vertical zones which:

(i) Are generally not more than 40 meters (131 feet) in mean length on any one deck;

(ii) Must be constructed to:

> (A) The greater of "A-30" Class or the requirements of paragraph (b) of this section, or;
>
> (B) Minimum "A-0" Class where there is a Type 8, 12 or 13 space on either side of the division; and

The CFR specifies specific fire boundaries via tables that cross reference "hot" and "cold" side space designations. Space designations are determined based on overall fire risk.

American Bureau of Shipping

The American Bureau of Shipping (ABS) is a nonprofit organization that develops rules for the classification of ship structures and equipment. ABS publishes about 90 different rules and guides, written in association with industry. Although ABS is primarily associated with large, steel ships, their involvement with small craft dates back to the 1920s, when a set of rules for wood sailing ship construction was published. The recent volume of work done for FRP yachts is summarized in Table 6-2. The publications and services offered by ABS are detailed below. [6-2]

Rules for Building and Classing Reinforced Plastic Vessels 1978

This publication gives hull structure, machinery and engineering system requirements for commercial displacement craft up to 200 feet in length. It contains comprehensive sections on materials and manufacture and is essentially for E-glass chopped strand mat and woven roving laminates with a means of approving other laminates given.

These general Rules have served and continue to service industry and ABS very well - they are adopted as Australian Government Regulations and are used by the USCG. They are applied currently by ABS to all commercial displacement craft in unrestricted ocean service.

Table 6-2 Statistics on ABS Services for FRP Yachts During the Past Decade [Curry, American Bureau of Shipping]

ABS Service	Sailing Yachts	Motor Yachts
Completed or contracted for class or hull certification as of 1989	336	94
Plan approval service only as of 1989	160	9
Currently in class (as of 1989)	121	164
Plan approval service from 1980 to 1989	390	35

Guide for Building and Classing Offshore Racing Yachts, 1986

This guide developed by ABS at the request of the Offshore Racing Council (ORC) 1978-1980 out of their concern for ever lighter advanced composite boats and the lack of suitable standards. At that time, several boats and lives had been lost. ABS staff referred to the design and construction practice for offshore racing yachts reflected in designers' and builders' practice and to limited full-scale measured load data and refined the results by analysis of many existing proven boats and analysis of damaged boat structures.

As the Guide was to provide for all possible hull materials, including advanced composites, it was essential that it be given in a direct engineering format of design loads and design stresses, based on ply, laminate and core material mechanical properties. Such a format permits the designer to readily see the influence of design loads, material mechanical properties and structural arrangement on the requirements, thereby giving as much freedom as possible to achieve optimum use of materials.

ABS is revising their approach for yachts, with special emphasis on vessels over 24 meters (78.7 feet). The initiative combines revised structural and machinery criteria and requirements for structural fire protection and one compartment damage stability. ABS will no longer offer other services (such as plan approval only) for yachts over 24 meters and no services for yachts under 24 meters will be available.

Guide for Building and Classing High Speed Craft

Since 1980, ABS has had specific in-house guidance for the hull structure of planing and semi-planing craft in commercial and government service. The *High-Speed Craft Guide* was first published in 1990 and is under revision for publication in 1997.

This Guide, for vessels up to 200 feet in length, covers glass fiber reinforced plastic, advanced composite, aluminum and steel hulls. Requirements are given in a direct engineering format expressed in terms of design pressures, design stresses, and material mechanical properties. Design planing slamming pressures for the bottom structure have been developed from the work of Heller and Jasper [6-3] Savitsky and Brown, [6-4] Allen and Jones [6-5], and Spencer [6-6]. Those for the side structure are based on a combination of hydrostatic and speed induced hydrodynamic pressures.

In establishing the bottom design pressures and dynamic components of side structure, distinction is made for example between passenger-carrying craft, general commercial craft, and mission type craft, such as patrol boats. Design pressures for decks, superstructures, houses and bulkheads are from ABS and industry practice.

Design stresses, have been obtained from ABS in-house guidance and from applying the various design pressures to many existing, proven vessels processed over the years by ABS. In providing requirements for advanced composites, criteria are given for strength in both 0° and 90° axes of structural panels.

Anticipating the desirability of extending the length of boats using standard or advanced composites, the Guide contains hull-girder strength requirements for vessels in both the displacement and planing modes. The former comes from current ABS Rules. The latter from Heller and Jasper bending moments together with hull-girder bending stresses obtained by applying these moments to many existing, proven planing craft designs. As might be expected, design stresses for the planing mode bending moments are relatively low, reflecting a need for design that accounts for fatigue strength.

Particularly for fiber reinforced plastic boats, criteria were established for hull-girder stiffness, by which, one of the potential limitations of fiber reinforced plastic, low tensile and compressive modulii, can be avoided by proper design.

Although the Guide contains specific, detailed standards for planing craft hull structures, it is not confined to these form hulls and operational modes. Brief, general requirements for surface effect, air cushion and hydrofoil craft are also included. The updated Guide will cover monohull vessels to 450 feet and catamarans to 350 feet. A dedicated machinery and structural fire protection section is to be added. Panel testing of hull bottom and topsides will be required, as will be builder's process descriptions. A laminate “stack” program will be included.

Guide for High Speed and Displacement Motor Yachts

As with high speed commercial and government service craft, ABS has utilized in-house guidance for many years for planing motor yachts. This has also been developed over the last few years into the *Guide for High Speed and Displacement Motor Yachts*.

The standards for high speed motor yachts parallel those for high speed commercial and government service craft and the preceding description of the Guide for the high speed commercial, patrol, and utility craft is equally applicable with the qualification that the design pressures for motor yachts reflect the less rigorous demands of this service.

Probably 80% to 90% of the motor yachts today are, by definition of this Guide, high speed. However to provide complete standards, the Guide also includes requirements for displacement motor yachts. Design loads and design stresses for these standards developed from *ABS Rules for Reinforced Plastic Vessels*, modified appropriately for advanced composite, aluminum and steel hulls and fine-tuned by review of a substantial number of existing proven, displacement hull motor yacht designs. In addition to hull structural standards, this Guide includes requirements for propulsion systems and essential engineering systems.

ABS has reviewed approximately 50 motor pleasure yachts since 1990. The average waterline length is 100 feet with a top speed of 24 knots. Figure 6-1 graphically depicts the ABS classification process.

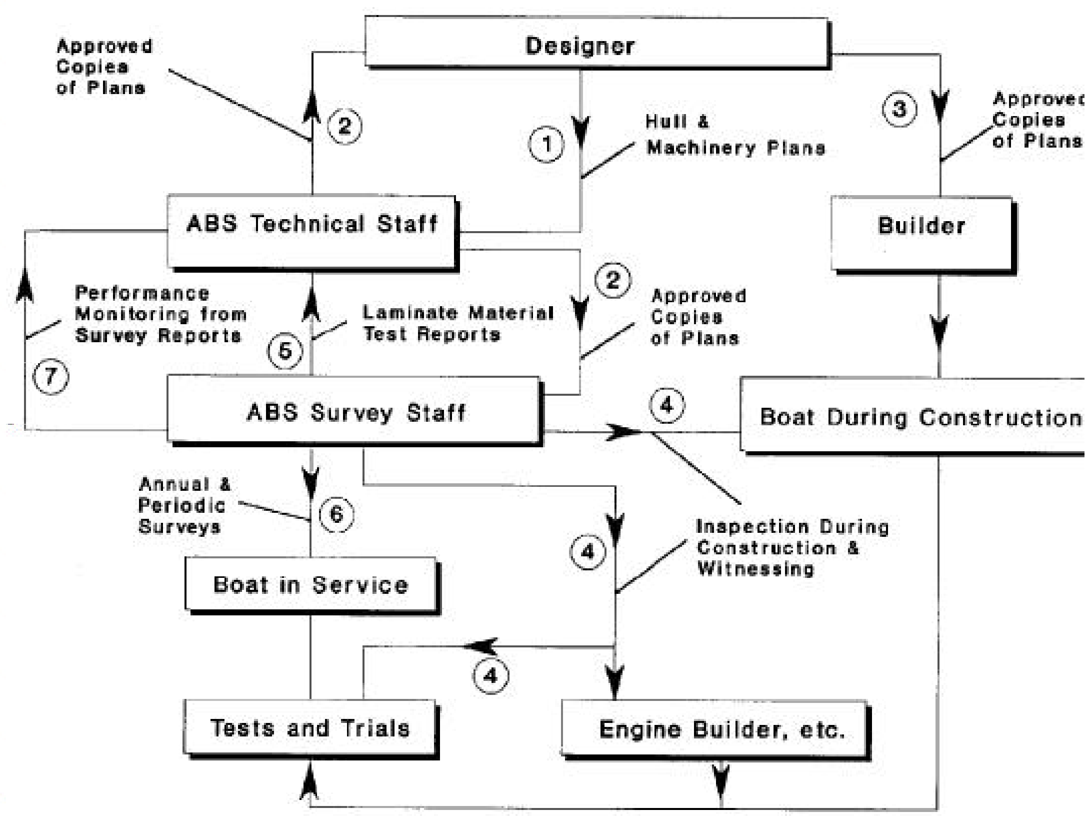


Figure 6-1 Flow Chart for ABS Classification Process [Curry, American Bureau of Shipping]

Conversion Factors

LENGTH		
Multiply:	**By:**	**To Obtain:**
Centimeters	0.0328	Feet
Centimeters	0.3937	Inches
Feet	30.4801	Centimeters
Feet	0.30480	Meters
Inches	2.54	Centimeters
Meters	3.28083	Feet
Meters	39.37	Inches
Meters	1.09361	Yards
Mils	0.001	Inches
Mils	25.40	Microns

MASS		
Multiply:	**By:**	**To Obtain:**
Grams	0.03527	Ounces*
Grams	2.205×10^{-3}	Pounds*
Kilograms	35.27	Ounces*
Kilograms	2.205	Pounds*
Kilograms	1.102×10^{-3}	Tons*
Kilograms	9.839×10^{-4}	Long Tons*
Long Tons*	1016	Kilograms
Long Tons*	2240	Pounds*
Metric Tons	2204.6	Pounds*
Ounces*	28.35	Grams
Pounds*	453.6	Grams
Pounds*	0.4536	Kilograms
Pounds*	0.0005	Tons*
Pounds*	4.464×10^{-4}	Long Tons*
Pounds*	4.536×10^{-4}	Metric Tons
Tons*	907.2	Kilograms
Tons*	2000	Pounds*

* These quantities are not mass units, but are often used as such. The conversion factors are based on $g = 32.174$ ft/sec^2.

AREA		
Multiply:	**By:**	**To Obtain:**
Square centimeters	1.0764×10^{-3}	Square feet
Square centimeters	0.15499	Square inches
Square centimeters^2 (moment of area)	0.02403	Square inches^2 (moment of area)
Square feet	0.09290	Square meters
Square feet	929.034	Square centimeters
Square feet^2 (moment of area)	20736	Square inches^2 (moment of area)
Square meters	10.76387	Square feet
Square meters	1550	Square inches
Square meters	1.196	Square yards
Square yards	1296	Square inches
Square yards	0.8361	Square meters

VOLUME		
Multiply:	**By:**	**To Obtain:**
Cubic centimeters	3.5314×10^{-5}	Cubic feet
Cubic centimeters	2.6417×10^{-4}	Gallons
Cubic centimeters	0.03381	Ounces
Cubic feet	28317.016	Cubic centimeters
Cubic feet	1728	Cubic inches
Cubic feet	7.48052	Gallons
Cubic feet	28.31625	Liters
Cubic inches	16.38716	Cubic centimeters
Cubic inches	0.55441	Ounces
Cubic meters	35.314	Cubic feet
Cubic meters	61023	Cubic inches
Cubic meters	1.308	Cubic yards
Cubic meters	264.17	Gallons
Cubic meters	999.973	Liters
Cubic yards	27	Cubic feet
Cubic yards	0.76456	Cubic meters

DENSITY		
Multiply:	**By:**	**To Obtain:**
Grams per centimeters^3	0.03613	Pounds per inches^3
Grams per centimeters^3	62.428	Pounds per feet^3
Kilograms per meters^3	3.613×10^{-5}	Pounds per inches^3
Kilograms per meters^3	0.06243	Pounds per feet3
Pounds per inches^3	2.768 x 104	Kilograms per meters^3
Pounds per inches^3	1728	Pounds per feet3
Pounds per feet^3	16.02	Kilograms per meters3
Pounds per feet^3	5.787×10^{-4}	Pounds per inches^3

FORCE		
Multiply:	**By:**	**To Obtain:**
Kilograms-force	9.807	Newtons
Kilograms-force	2.205	Pounds
Newtons	0.10197	Kilograms-force
Newtons	0.22481	Pounds
Pounds	4.448	Newtons
Pounds	0.4536	Kilograms-force

PRESSURE		
Multiply:	**By:**	**To Obtain:**
Feet of saltwater (head)	3064.32	Pascals
Feet of saltwater (head)	64	Pounds per feet^2
Feet of saltwater (head)	0.44444	Pounds per inches^2
Inches of water	249.082	Pascals
Inches of water	5.202	Pounds per feet^2
Inches of water	0.03613	Pounds per inches^2
Pascals	0.02089	Pounds per feet^2
Pascals	1.4504×10^{-4}	Pounds per inches^2
Pounds per feet^2	47.88	Pascals
Pounds per feet^2	6.944 x 10-3	Pounds per inches^2
Pounds per inches^2	6895	Pascals
Pounds per inches^2	144	Pounds per feet^2
Pascals = Newtons per meters^2		

Weights and Conversion Factors [*Principles of Naval Architecture*]

Quantity	Water		Oil			Gasoline
	Salt	Fresh	Fuel	Diesel	Lube	
Cubic feet per long ton	35	36	38	41.5	43	50
Gallons per long ton	—	269.28	284.24	310.42	321.64	374.00
Barrels per long ton	—	—	6.768	7.391	7.658	8.905
Pounds per gallon	—	—	7.881	7.216	6.964	5.989
Pounds per cubic feet	64	62.222	58.947	53.976	52.093	44.800
Pounds per barrel	—	—	331	303	292.5	251.5

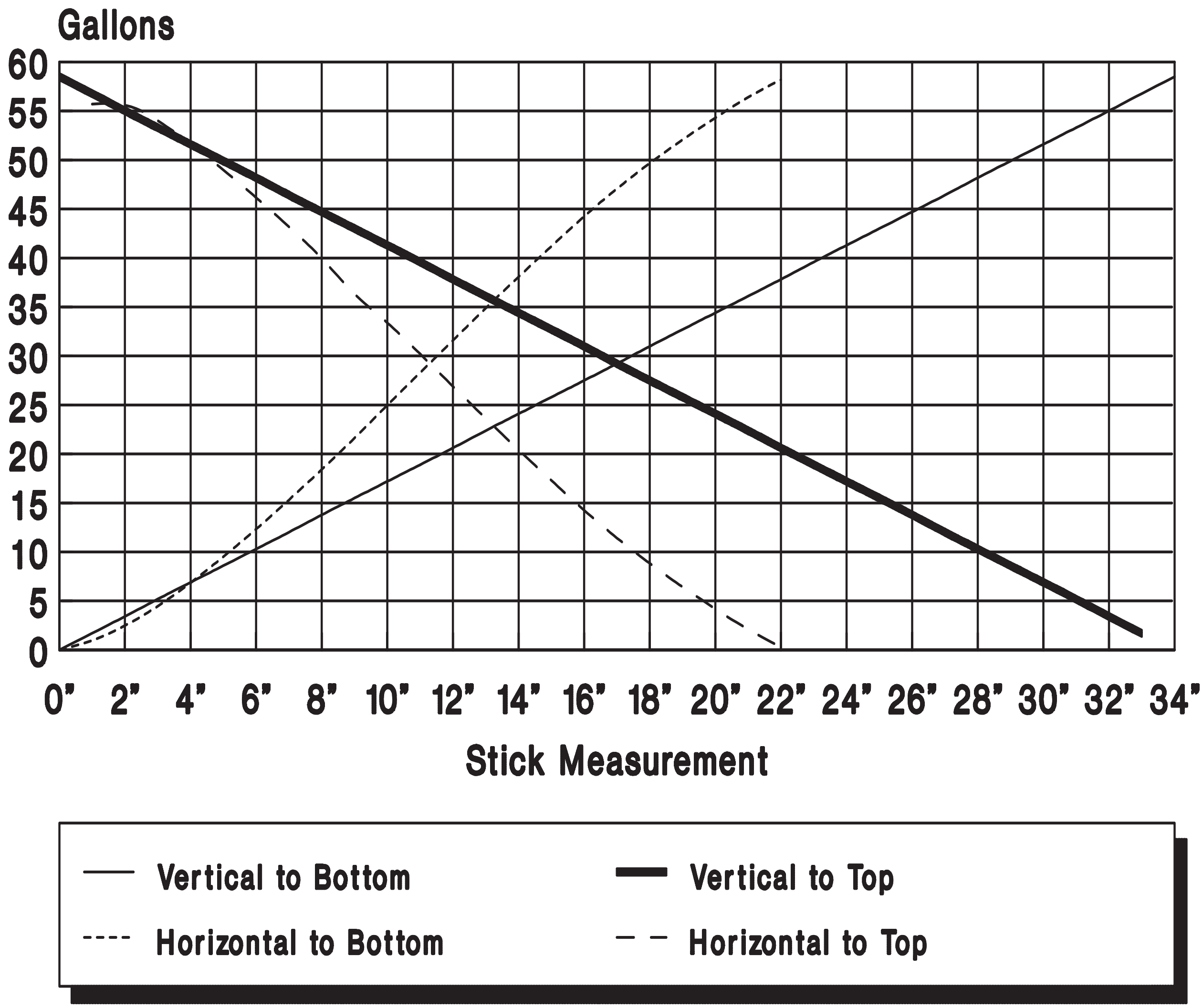


Figure 6-2 Volume Remaining in a 55 Gallon Drum based on Ruler Measurements from the Top and Bottom for Horizontal and Vertical Drums [Cook, *Polycor Polyester Gel Coats and Resins*]

Polyester Resin Conversion Factors
[Cook, *Polycor Polyester Gel Coats and Resins*]

Multiply:	By:	To Obtain:
Fluid ounces MEK Peroxide*	32.2	Grams MEK Peroxide*
Grams MEK Peroxide*	.0309	Fluid ounces MEK Peroxide*
Cubic centimeters MEK Peroxide*	1.11	Grams MEK Peroxide*
Grams MEK Peroxide*	0.90	Cubic centimeters MEK Peroxide*
Fluid ounces cobalt**	30.15	Grams cobalt**
Grams cobalt**	0.033	Fluid ounces cobalt**
Grams cobalt**	0.98	Cubic centimeters cobalt**
Gallon polyester resin†	9.2	Pounds
Gallon polyester resin†	13.89	Fluid ounces
Gallon polyester resin†	411	Cubic centimeters

* 9% Active Oxygen
** 6% Solution
† Unpigmented

Material Coverage Assuming No Loss
[Cook, *Polycor Polyester Gel Coats and Resins*]

Wet Film Thickness		Ft^2 per Gallon	Gallons per 1000 Ft^2
Inches	Mils		
.001	1	1600.0	0.63
.003	3	534.0	1.90
.005	5	320.0	3.10
.010	10	160.0	6.30
.015	15	107.0	9.40
.018	18	89.0	11.20
.020	20	80.0	12.50
.025	25	64.0	15.60
.030	30	53.0	19.00
.031	31	51.0	19.50
.060	60	27.0	38.00
.062	62	26.0	39.00

GLOSSARY

A

ablation The degradation, decomposition and erosion of material caused by high temperature, pressure, time, percent oxidizing species and velocity of gas flow. A controlled loss of material to protect the underlying structure.

ablative plastic A material that absorbs heat (with a low material loss and char rate) through a decomposition process (pyrolysis) that takes place at or near the surface exposed to the heat.

absorption The penetration into the mass of one substance by another. The capillary or cellular attraction of adherend surfaces to draw off the liquid adhesive film into the substrate.

accelerated test A test procedure in which conditions are increased in magnitude to reduce the time required to obtain a result. To reproduce in a short time the deteriorating effect obtained under normal service conditions.

accelerator A material that, when mixed with a catalyst or resin, will speed up the chemical reaction between the catalyst and the resin (either polymerizing of resins or vulcanization of rubbers). Also called promoter.

acceptance test A test, or series of tests, conducted by the procuring agency upon receipt of an individual lot of materials to determine whether the lot conforms to the purchase order or contract or to determine the degree of uniformity of the material supplied by the vendor, or both.

acetone In an FRP context, acetone is primarily useful as a cleaning solvent for removal of uncured resin from applicator equipment and clothing. This is a very flammable liquid.

acoustic emission A measure of integrity of a material, as determined by sound emission when a material is stressed. Ideally, emissions can be correlated with defects and/or incipient failure.

activator An additive used to promote and reduce the curing time of resins. See also accelerator.

additive Any substance added to another substance, usually to improve properties, such as plasticizers, initiators, light stabilizers and flame retardants.

adherend A body that is held to another body, usually by an adhesive. A detail or part prepared for bonding.

advanced composites Strong, tough materials created by combining one or more stiff, high-strength reinforcing fiber with compatible resin system. Advanced composites can be substituted for metals in many structural applications with physical properties comparable or better than aluminum.

air-inhibited resin A resin by which surface cures will be inhibited or stopped in the presence of air.

aging The effect on materials of exposure to an environment for an interval of time. The process of exposing materials to an environment for a interval of time.

air-bubble void Air entrapment within and between the plies of reinforcement or within a bondline or encapsulated area; localized, noninterconnected, spherical in shape.

allowables Property values used for design with a 95 percent confidence interval: the “A” allowable is the minimum value for 99 percent of the population; and the “B” allowable, 90 percent.

alternating stress A stress varying between two maximum values which are equal but with opposite signs, according to a law determined in terms of the time.

alternating stress amplitude A test parameter of a dynamic fatigue test: one-half the algebraic difference between the maximum and minimum stress in one cycle.

ambient conditions Prevailing environmental conditions such as the surrounding temperature, pressure and relative humidity.

anisotropic Not isotropic. Exhibiting different properties when tested along axes in different directions.

antioxidant A substance that, when added in small quantities to the resin during mixing, prevents its oxidative degradation and contributes to the maintenance of its properties.

aramid A type of highly oriented organic material derived from polyamide (nylon) but incorporating aromatic ring structure. Used primarily as a high-strength high-modulus fiber. Kevlar® and Nomex® are examples of aramids.

areal weight The weight of fiber per unit area (width x length) of tape or fabric.

artificial weathering The exposure of plastics to cyclic, laboratory conditions, consisting of high and low temperatures, high and low relative humidities, and ultraviolet radiant energy, with or without direct water spray and moving air (wind), in an attempt to produce changes in their properties similar to those observed in long-term continuous exposure outdoors. The laboratory exposure conditions are usually intensified beyond those encountered in actual outdoor exposure, in an attempt to achieve an accelerated effect.

aspect ratio The ratio of length to diameter of a fiber or the ratio of length to width in a structural panel.

autoclave A closed vessel for conducting and completing a chemical reaction or other operation, such as cooling, under pressure and heat.

B

bagging Applying an impermeable layer of film over an uncured part and sealing the edges so that a vacuum can be drawn.

balanced construction Equal parts of warp and fill in fiber fabric. Construction in which reactions to tension and compression loads result in extension or compression deformations only and in which flexural loads produce pure bending of equal magnitude in axial and lateral directions.

balanced laminate A composite in which all laminae at angles other than 0^o and 90^o occur only in ± pairs (not necessarily adjacent) and are symmetrical around the centerline.

Barcol hardness A hardness value obtained by measuring the resistance to penetration of a sharp steel point under a spring load. The instrument, called a Barcol impressor, gives a direct reading on a scale of 0 to 100. The hardness value is often used as a measure of the degree of cure of a plastic.

barrier film The layer of film used to permit removal of air and volatiles from a composite lay-up during cure while minimizing resin loss.

bedding compound White lead or one of a number of commercially available resin compounds used to form a flexible, waterproof base to set fittings.

bias fabric Warp and fill fibers at an angle to the length of the fabric.

biaxial load A loading condition in which a laminate is stressed in two different directions in its plane.

bidirectional laminate A reinforced plastic laminate with the fibers oriented in two directions in its plane. A cross laminate.

binder The resin or cementing constituent (of a plastic compound) that holds the other components together. The agent applied to fiber mat or preforms to bond the fibers before laminating or molding.

bleeder cloth A woven or nonwoven layer of material used in the manufacture of composite parts to allow the escape of excess gas and resin during cure. The bleeder cloth is removed after the curing process and is not part of the final composite.

blister An elevation on the surface of an adherend containing air or water vapor, somewhat resembling in shape a blister on the human skin. Its boundaries may be indefinitely outlined, and it may have burst and become flattened.

bond The adhesion at the interface between two surfaces. To attach materials together by means of adhesives.

bond strength The amount of adhesion between bonded surfaces. The stress required to separate a layer of material from the base to which it is bonded, as measured by load/bond area. See also peel strength.

bonding angles An additional FRP laminate, or an extension of the laminate used to make up the joined member, which extends onto the existing laminate to attach additional items such as framing, bulkheads and shelves to the shell or to each other.

boundary conditions Load and environmental conditions that exist at the boundaries. Conditions must be specified to perform stress analysis.

buckling A mode of failure generally characterized by an unstable lateral material deflection due to compressive action on the structural element involved.

bulk molding compound (BMC) Thermo-set resin mixed with strand reinforcement, fillers, etc. into a viscous compound for compression or injection molding.

butt joint A type of edge joint in which the edge faces of the two adherends are at right angles to the other faces of the adherends.

C

carbon The element that provides the backbone for all organic polymers. Graphite is a more ordered form of carbon. Diamond is the densest crystalline form of carbon.

carbon fiber Fiber produced by the pyrolysis of organic precursor fibers, such as rayon, polyacrylonitrile (PAN), and pitch, in an inert environment. The term is often used interchangeably with the term graphite; however carbon fibers and graphite fibers differ. The basic differences lie in the temperature at which the fibers are made and heat treated, and in the amount of elemental carbon produced. Carbon fibers typically are carbonized in the region of 2400°F and assay at 93 to 95% carbon, while graphite fibers are graphitized between 3450° and 4500°F and assay to more than 99% elemental carbon.

carpet plot A design chart showing the uniaxial stiffness or strength as a function of arbitrary ratios of 0, 90, and ±45 degree plies.

catalyst A substance that changes the rate of a chemical reaction without itself undergoing permanent change in composition or becoming a part of the molecular structure of the product. A substance that markedly speeds up the cure of a compound when added in minor quantity.

cell In honeycomb core, a cell is a single honeycomb unit, usually in a hexagonal shape.

cell size The diameter of an inscribed circle within the cell of a honeycomb core.

Charpy impact test A test for shock loading in which a centrally notched sample bar is held at both ends and broken by striking the back face in the same plane as the notch.

chain plates The metallic plates, embedded in or attached to the hull or bulkhead, used to evenly distribute loads from shrouds and stays to the hull of sailing vessels.

chopped strand Continuous strand yarn or roving cut up into uniform lengths, usually from $\frac{1}{32}$ inch long. Lengths up to $\frac{1}{8}$ inch are called milled fibers.

closed cell foam Cellular plastic in which individual cells are completely sealed off from adjacent cells.

cocuring The act of curing a composite laminate and simultaneously bonding it to some other prepared surface. See also secondary bonding.

coin test Using a coin to test a laminate in different spots, listening for a change in sound, which would indicate the presence of a defect. A surprisingly accurate test in the hands of experienced personnel.

compaction The application of a temporary vacuum bag and vacuum to remove trapped air and compact the lay-up.

compliance Measurement of softness as opposed to stiffness of a material. It is a reciprocal of the Young's modulus, or an inverse of the stiffness matrix.

composite material A combination of two or more materials (reinforcing elements, fillers and composite matrix binder), differing in form or composition on a macroscale. The constituents retain their identities; that is, they do not dissolve or merge completely into one another although they act in concert. Normally, the components can be physically identified and exhibit an interface between one another.

compression molding A mold that is open when the material is introduced and that shapes the material by the presence of closing and heat.

compressive strength The ability of a material to resist a force that tends to crush or buckle. The maximum compressive load sustained by a specimen divided by the original cross-sectional area of the specimen.

compressive stress The normal stress caused by forces directed toward the plane on which they act.

contact molding A process for molding reinforced plastics in which reinforcement and resin are placed on a mold. Cure is either at room temperature using a catalyst-promoter system or by heating in an oven, without additional pressure.

constituent materials Individual materials that make up the composite material; e.g., graphite and epoxy are the constituent materials of a graphite/epoxy composite material.

copolymer A long chain molecule formed by the reaction of two or more dissimilar monomers.

core The central member of a sandwich construction to which the faces of the sandwich are attached. A channel in a mold for circulation of heat-transfer media. Male part of a mold which shapes the inside of the mold.

corrosion resistance The ability of a material to withstand contact with ambient natural factors or those of a particular artificially created atmosphere, without degradation or change in properties. For metals, this could be pitting or rusting; for organic materials, it could be crazing.

count For fabric, number of warp and filling yarns per inch in woven cloth. For yarn, size based on relation of length and weight.

coupling agent Any chemical agent designed to react with both the reinforcement and matrix phases of a composite material to form or promote a stronger bond at the interface.

crazing Region of ultrafine cracks, which may extend in a network on or under the surface of a resin or plastic material. May appear as a white band.

creep The change in dimension of a material under load over a period of time, not including the initial instantaneous elastic deformation. (Creep at room temperature is called cold flow.) The time dependent part of strain resulting from an applied stress.

cross-linking Applied to polymer molecules, the setting-up of chemical links between the molecular chains. When extensive, as in most thermosetting resins, cross-linking makes one infusible supermolecule of all the chains.

C-scan The back-and-forth scanning of a specimen with ultrasonics. A nondestructive testing technique for finding voids, delaminations, defects in fiber distribution, and so forth.

cure To irreversibly change the properties of a thermosetting resin by chemical reaction, i.e. condensation, ring closure or addition. Curing may be accomplished by addition of curing (crosslinking) agents, with or without heat.

curing agent A catalytic or reactive agent that, when added to a resin, causes polymerization. Also called a hardener.

D

damage tolerance A design measure of crack growth rate. Cracks in damage tolerant designed structures are not permitted to grow to critical size during expected service life.

delamination Separation of the layers of material in a laminate, either local or covering a wide area. Can occur in the cure or subsequent life.

debond Area of separation within or between plies in a laminate, or within a bonded joint, caused by contamination, improper adhesion during processing or damaging interlaminar stresses.

denier A yarn and filament numbering system in which the yarn number is numerically equal to the weight in grams of 9000 meters. Used for continuous filaments where the lower the denier, the finer the yarn.

dimensional stability Ability of a plastic part to retain the precise shape to which it was molded, cast or otherwise fabricated.

dimples Small sunken dots in the gel coat surface, generally caused by a foreign particle in the laminate.

draft angle The angle of a taper on a mandrel or mold that facilitates removal of the finished part.

drape The ability of a fabric or a prepreg to conform to a contoured surface.

dry laminate A laminate containing insufficient resin for complete bonding of the reinforcement. See also resin-starved area.

ductility The amount of plastic strain that a material can withstand before fracture. Also, the ability of a material to deform plastically before fracturing.

E

E-glass A family of glasses with a calcium aluminoborosilicate composition and a maximum alkali content of 2.0%. A general-purpose fiber that is most often used in reinforced plastics, and is suitable for electrical laminates because of its high resistivity. Also called electric glass.

elastic deformation The part of the total strain in a stressed body that disappears upon removal of the stress.

elasticity That property of materials by virtue of which they tend to recover their original size and shape after removal of a force causing deformation.

elastic limit The greatest stress a material is capable of sustaining without permanent strain remaining after the complete release of the stress. A material is said to have passed its elastic limit when the load is sufficient to initiate plastic, or nonrecoverable, deformation.

elastomer A material that substantially recovers its original shape and size at room temperature after removal of a deforming force.

elongation Deformation caused by stretching. The fractional increase in length of a material stressed in tension. (When expressed as percentage of the original gage length, it is called percentage elongation.)

encapsulation The enclosure of an item in plastic. Sometimes used specifically in reference to the enclosure of capacitors or circuit board modules.

epoxy plastic A polymerizable thermoset polymer containing one or more epoxide groups and curable by reaction with amines, alcohols, phenols, carboxylic acids, acid anhydrides, and mercaptans. An important matrix resin in composites and structural adhesive.

exotherm heat The heat given off as the result of the action of a catalyst on a resin.

F

failure criterion Empirical description of the failure of composite materials subjected to complex state of stresses or strains. The most commonly used are the maximum stress, the maximum strain, and the quadratic criteria.

failure envelope Ultimate limit in combined stress or strain state defined by a failure criterion.

fairing A member or structure, the primary function of which is to streamline the flow of a fluid by producing a smooth outline and to reduce drag, as in aircraft frames and boat hulls.

fatigue The failure or decay of mechanical properties after repeated applications of stress. Fatigue tests give information on the ability of a material to resist the development of cracks, which eventually bring about failure as a result of a large number of cycles.

fatigue life The number of cycles of deformation required to bring about failures of the test specimen under a given set of oscillating conditions (stresses or strains).

fatigue limit The stress limit below which a material can be stressed cyclically for an infinite number of times without failure.

fatigue strength The maximum cyclical stress a material can withstand for a given number of cycles before failure occurs. The residual strength after being subjected to fatigue.

faying surface The surfaces of materials in contact with each other and joined or about to be joined together.

felt A fibrous material made up of interlocking fibers by mechanical or chemical action, pressure or heat. Felts may be made of cotton, glass or other fibers.

fiber A general term used to refer to filamentary materials. Often, fiber is used synonymously with filament. It is a general term for a filament with a finite length that is at least 100 times its diameter, which is typically 0.004 to 0.005 inches. In most cases it is prepared by drawing from a molten bath, spinning, or deposition on a substrate. A whisker, on the other hand, is a short single-crystal fiber or filament made from a variety of materials, with diameters ranging from 40 to 1400 micro inches and aspect ratios between 100 and 15000. Fibers can be continuous or specific short lengths (discontinuous), normally less than $\frac{1}{8}$ inch.

fiber content The amount of fiber present in a composite. This is usually expressed as a percentage volume fraction or weight fraction of the composite.

fiber count The number of fibers per unit width of ply present in a specified section of a composite.

fiber direction The orientation or alignment of the longitudinal axis of the fiber with respect to a stated reference axis.

fiberglass An individual filament made by drawing molten glass. A continuous filament is a glass fiber of great or indefinite length. A staple fiber is a glass fiber of relatively short length, generally less than 17 inches, the length related to the forming or spinning process used.

fiberglass reinforcement Major material used to reinforce plastic. Available as mat, roving, fabric, and so forth, it is incorporated into both thermosets and thermoplastics.

fiber-reinforced plastic (FRP) A general term for a composite that is reinforced with cloth, mat, strands or any other fiber form.

fiberglass chopper Chopper guns, long cutters and roving cutters cut glass into strands and fibers to be used as reinforcement in plastics.

Fick's equation Diffusion equation for moisture migration. This is analogous to the Fourier's equation of heat conduction.

filament The smallest unit of fibrous material. The basic units formed during drawing and spinning, which are gathered into strands of fiber for use in composites. Filaments usually are of extreme length and very small diameter, usually less than 1 mil. Normally, filaments are not used individually. Some textile filaments can function as a yarn when they are of sufficient strength and flexibility.

filament winding A process for fabricating a composite structure in which continuous reinforcements (filament, wire, yarn, tape or other) either previously impregnated with a matrix material or impregnated during the winding, are placed over a rotating and removable form or mandrel in a prescribed way to meet certain stress conditions. Generally, the shape is a surface of revolution and may or may not include end closures. When the required number of layers is applied, the wound form is cured and the mandrel is removed.

fill Yarn oriented at right angles to the warp in a woven fabric.

filler A relatively inert substance added to a material to alter its physical, mechanical, thermal, electrical and other properties or to lower cost or density. Sometimes the term is used specifically to mean particulate additives.

fillet A rounded filling or adhesive that fills the corner or angle where two adherends are joined.

filling yarn The transverse threads or fibers in a woven fabric. Those fibers running perpendicular to the warp. Also called weft.

finish A mixture of materials for treating glass or other fibers. It contains a coupling agent to improve the bond of resin to the fiber, and usually includes a lubricant to prevent abrasion, as well as a binder to promote strand integrity. With graphite or other filaments, it may perform any or all of the above functions.

first-ply-failure First ply or ply group that fails in a multidirectional laminate. The load corresponding to this failure can be the design limit load.

flame retardants Certain chemicals that are used to reduce or eliminate the tendency of a resin to burn.

fish eye A circular separation in a gel coat film generally caused by contamination such as silicone, oil, dust or water.

flammability Measure of the extent to which a material will support combustion.

flexural modulus The ratio, within the elastic limit, of the applied stress on a test specimen in flexure to the corresponding strain in the outermost fibers of the specimen.

flexural strength The maximum stress that can be borne by the surface fibers in a beam in bending. The flexural strength is the unit resistance to the maximum load before failure by bending, usually expressed in force per unit area.

flow The movement of resin under pressure, allowing it to fill all parts of the mold. The gradual but continuous distortion of a material under continued load, usually at high temperatures; also called creep.

foam-in-place Refers to the deposition of foams when the foaming machine must be brought to the work that is “in place,” as opposed to bringing the work to the foaming machine. Also, foam mixed in a container and poured in a mold, where it rises to fill the cavity.

fracture toughness A measure of the damage tolerance of a material containing initial flaws or cracks. Used in aircraft structural design and analysis.

G

gel The initial jellylike solid phase that develops during the formation of a resin from a liquid. A semisolid system consisting of a network of solid aggregates in which liquid is held.

gelation time That interval of time, in connection with the use of synthetic thermosetting resins, extending from the introduction of a catalyst into a liquid adhesive system until the start of gel formation. Also, the time under application of load for a resin to reach a solid state.

gel coat A quick setting resin applied to the surface of a mold and gelled before lay-up. The gel coat becomes an integral part of the finish laminate, and is usually used to improve surface appearance and bonding.

glass finish A material applied to the surface of a glass reinforcement to improve the bond between the glass and the plastic resin matrix.

glass transition The reversible change in an amorphous polymer or in an amorphous regions of a partially crystalline polymer from, or to, a viscous or rubbery condition to, or from, a hard to a relatively brittle one.

graphite To crystalline allotropic form of carbon.

green strength The ability of a material, while not completely cured, set or sintered, to undergo removal from the mold and handling without distortion.

H

hand lay-up The process of placing (and working) successive plies of reinforcing material of resin-impregnated reinforcement in position on a mold by hand.

hardener A substance or mixture added to a plastic composition to promote or control the curing action by taking part in it.

harness satin Weaving pattern producing a satin appearance. "Eight-harness" means the warp tow crosses over seven fill tows and under the eighth (repeatedly).

heat build-up The temperature rise in part resulting from the dissipation of applied strain energy as heat.

heat resistance The property or ability of plastics and elastomers to resist the deteriorating effects of elevating temperatures.

homogeneous Descriptive term for a material of uniform composition throughout. A medium that has no internal physical boundaries. A material whose properties are constant at every point, that is, constant with respect to spatial coordinates (but not necessarily with respect to directional coordinates).

honeycomb Manufactured product of resin impregnated sheet material (paper, glass fabric and so on) or metal foil, formed into hexagonal-shaped cells. Used as a core material in sandwich constructions.

hoop stress The circumferential stress in a material of cylindrical form subjected to internal or external pressure.

hull liner A separate interior hull unit with bunks, berths, bulkheads, and other items of outfit preassembled then inserted into the hull shell. A liner can contribute varying degrees of stiffness to the hull through careful arrangement of the berths and bulkheads.

hybrid A composite laminate consisting of laminae of two or more composite material systems. A combination of two or more different fibers, such as carbon and glass or carbon and aramid, into a structure. Tapes, fabrics and other forms may be combined; usually only the fibers differ.

hygrothermal effect Change in properties due to moisture absorption and temperature change.

hysteresis The energy absorbed in a complete cycle of loading and unloading. This energy is converted from mechanical to frictional energy (heat).

I

ignition loss The difference in weight before and after burning. As with glass, the burning off of the binder or size.

impact strength The ability of a material to withstand shock loading. The work done on fracturing a test specimen in a specified manner under shock loading.

impact test Measure of the energy necessary to fracture a standard notched bar by an impulse load.

impregnate In reinforced plastics, to saturate the reinforcement with a resin.

inclusion A physical and mechanical discontinuity occurring within a material or part, usually consisting of solid, encapsulated foreign material. Inclusions are often capable of transmitting some structural stresses and energy fields, but in a noticeably different degree from the parent material.

inhibitor A material added to a resin to slow down curing. It also retards polymerization, thereby increasing shelf life of a monomer.

injection molding Method of forming a plastic to the desired shape by forcing the heat-softened plastic into a relatively cool cavity under pressure.

interlaminar Descriptive term pertaining to an object (for example, voids), event (for example, fracture), or potential field (for example, shear stress) referenced as existing or occurring between two or more adjacent laminae.

interlaminar shear Shearing force tending to produce a relative displacement between two laminae in a laminate along the plane of their interface.

intralaminar Descriptive term pertaining to an object (for example, voids), event (for example, fracture), or potential field (for example, temperature gradient) existing entirely within a single lamina without reference to any adjacent laminae.

isotropic Having uniform properties in all directions. The measured properties of an isotropic material are independent of the axis of testing.

Izod impact test A test for shock loading in which a notched specimen bar is held at one end and broken by striking, and the energy absorbed is measured.

K

kerf The width of a cut made by a saw blade, torch, water jet, laser beam and so forth.

Kevlar® An organic polymer composed of aromatic polyamides having a para-type orientation (parallel chain extending bonds from each aromatic nucleus).

knitted fabrics Fabrics produced by interlooping chains of yarn.

L

lamina A single ply or layer in a laminate made up of a series of layers (organic composite). A flat or curved surface containing unidirectional fibers or woven fibers embedded in a matrix.

laminae Plural of lamina

laminate To unite laminae with a bonding material, usually with pressure and heat (normally used with reference to flat sheets, but also rods and tubes). A product made by such bonding.

lap joint A joint made by placing one adherend partly over another and bonding the overlapped portions.

lay-up The reinforcing material placed in position in the mold. The process of placing the reinforcing material in a position in the mold. The resin-impregnated reinforcement. A description of the component materials, geometry, and so forth, of a laminate.

load-deflection curve A curve in which the increasing tension, compression, or flexural loads are plotted on the ordinate axis and the deflections caused by those loads are plotted on the abscissa axis.

loss on ignition Weight loss, usually expressed as percent of total, after burning off an organic sizing from glass fibers, or an organic resin from a glass fiber laminate.

low-pressure laminates In general, laminates molded and cured in the range of pressures from 400 psi down to and including pressure obtained by the mere contact of the plies.

M

macromechanics Structural behavior of composite laminates using the laminated plate theory. The fiber and matrix within each ply are smeared and no longer identifiable.

mat A fibrous material for reinforced plastic consisting of randomly oriented chopped filaments, short fibers (with or without a carrier fabric), or swirled filaments loosely held together with a binder. Available in blankets of various widths, weights and lengths. Also, a sheet formed by filament winding a single-hoop ply of fiber on a mandrel, cutting across its width and laying out a flat sheet.

matrix The essentially homogeneous resin or polymer material in which the fiber system of a composite is embedded. Both thermoplastic and thermoset resins may be used, as well as metals, ceramics and glass.

mechanical adhesion Adhesion between surfaces in which the adhesive holds the parts together by interlocking action.

mechanical properties The properties of a material, such as compressive or tensile strength, and modulus, that are associated with elastic and inelastic reaction when force is applied. The individual relationship between stress and strain.

mek peroxide (MEKP) Abbreviation for Methyl Ethyl Ketone Peroxide; a strong oxidizing agent (free radical source) commonly used as the catalyst for polyesters in the FRP industry.

micromechanics Calculation of the effective ply properties as functions of the fiber and matrix properties. Some numerical approaches also provide the stress and strain within each constituent and those at the interface.

mil The unit used in measuring the diameter of glass fiber strands, wire, etc. (1 mil = 0.001 inch).

milled fiber Continuous glass strands hammer milled into very short glass fibers. Useful as inexpensive filler or anticrazing reinforcing fillers for adhesives.

modulus of elasticity The ratio of stress or load applied to the strain or deformation produced in a material that is elasticity deformed. If a tensile strength of 2 ksi results in an elongation of 1%, the modulus of elasticity is 2.0 ksi divided by 0.01 or 200 ksi. Also called Young's modulus.

moisture absorption The pickup of water vapor from air by a material. It relates only to vapor withdrawn from the air by a material and must be distinguished from water absorption, which is the gain in weight due to the take-up of water by immersion.

moisture content The amount of moisture in a material determined under prescribed conditions and expressed as a percentage of the mass of the moist specimen, that is, the mass of the dry substance plus the moisture present.

mold The cavity or matrix into or on which the plastic composition is placed and from which it takes form. To shape plastic parts or finished articles by heat and pressure. The assembly of all parts that function collectively in the molding process.

mold-release agent A lubricant, liquid or powder (often silicone oils and waxes), used to prevent the sticking of molded articles in the cavity.

monomer A single molecule that can react with like or unlike molecules to form a polymer. The smallest repeating structure of a polymer (mer). For additional polymers, this represents the original unpolymerized compound.

N

netting analysis Treating composites like fibers without matrix. It is not a mechanical analysis, and is not applicable to composites.

non-air-inhibited resin A resin in which the surface cure will not be inhibited or stopped by the presence of air. A surfacing agent has been added to exclude air from the surface of the resin.

nondestructive evaluation (NDE) Broadly considered synonymous with nondestructive inspection (NDI). More specifically, the analysis of NDI findings to determine whether the material will be acceptable for its function.

nondestructive inspection (NDI) A process or procedure, such as ultrasonic or radiographic inspection, for determining the quality of characteristics of a material, part or assembly, without permanently altering the subject or its properties. Used to find internal anomalies in a structure without degrading its properties.

nonwoven fabric A planar textile structure produced by loosely compressing together fibers, yarns, rovings, etc. with or without a scrim cloth carrier. Accomplished by mechanical, chemical, thermal, or solvent means and combinations thereof.

non-volatile material Portion remaining as solid under specific conditions short of decomposition.

normal stress The stress component that is perpendicular to the plane on which the forces act.

notch sensitivity The extent to which the sensitivity of a material to fracture is increased by the presence of a surface nonhomogeneity, such as a notch, a sudden change in section, a crack or a scratch. Low notch sensitivity is usually associated with ductile materials, and high notch sensitivity is usually associated with brittle materials.

O

orange peel Backside of the gel coated surface that takes on the rough wavy texture of an orange peel.

orthotropic Having three mutually perpendicular planes of elastic symmetry.

P

panel The designation of a section of FRP shell plating, of either single-skin or sandwich construction, bonded by longitudinal and transverse stiffeners or other supporting structures.

peel ply A layer of resin-free material used to protect a laminate for later secondary bonding.

peel strength Adhesive bond strength, as in pounds per inch of width, obtained by a stress applied in a peeling mode.

permanent set The deformation remaining after a specimen has been stressed a prescribed amount in tension, compression or shear for a definite time period. For creep tests, the residual unrecoverable deformation after the load causing the creep has been removed for a substantial and definite period of time. Also, the increase in length, by which an elastic material fails to return to original length after being stressed for a standard period of time.

permeability The passage or diffusion (or rate of passage) of gas, vapor, liquid or solid through a barrier without physically or chemically affecting it.

phenolic (phenolic resin) A thermosetting resin produced by the condensation of an aromatic alcohol with an aldehyde, particularly of phenol with formaldehyde. Used in high- temperature applications with various fillers and reinforcements.

pitch A high molecular weight material left as a residue from the destructive distillation of coal and petroleum products. Pitches are used as base materials for the manufacture of certain high-modulus carbon fibers and as matrix precursors for carbon-carbon composites.

plasticity A property of adhesives that allows the material to be deformed continuously and permanently without rupture upon the application of a force that exceeds the yield value of the material.

plain weave A weaving pattern in which the warp and fill fibers alternate; that is, the repeat pattern is warp/fill/warp/fill. Both faces of a plain weave are identical. Properties are significantly reduced relative to a weaving pattern with fewer crossovers.

ply In general, fabrics or felts consisting of one or more layers (laminates). The layers that make up a stack. A single layer of prepreg.

Poisson's ratio The ratio of the change in lateral width per unit width to change in axial length per unit length caused by the axial stretching or stressing of the material. The ratio of transverse strain to the corresponding axial strain below the proportional limit.

polyether etherketone (PEEK) A linear aromatic crystalline thermoplastic. A composite with a PEEK matrix may have a continuous use temperature as high as 480^{o}F.

polymer A high molecular weight organic compound, natural or synthetic, whose structure can be represented by a repeated small unit, the mer. Examples include polyethylene, rubber and cellulose. Synthetic polymers are formed by addition or condensation polymerization of monomers. Some polymers are elastomers, some are plastics and some are fibers. When two or more dissimilar monomers are involved, the product is called a copolymer. The chain lengths of commercial thermoplastics vary from near a thousand to over one hundred thousand repeating units. Thermosetting polymers approach infinity after curing, but their resin precursors, often called prepolymers, may be a relatively short six to one hundred repeating units before curing. The lengths of polymer chains, usually measured by molecular weight, have very significant effects on the performance properties of plastics and profound effects on processibility.

polymerization A chemical reaction in which the molecules of a monomer are linked together to form large molecules whose molecular weight is a multiple of that of the original substance. When two or more monomers are involved, the process is called copolymerization.

polyurethane A thermosetting resin prepared by the reaction of disocyanates with polols, polyamides, alkyd polymers and plyether polymers.

porosity Having voids; i.e., containing pockets of trapped air and gas after cure. Its measurement is the same as void content. It is commonly assumed that porosity is finely and uniformly distributed throughout the laminate.

postcure Additional elevated-temperature cure, usually without pressure, to improve final properties and/or complete the cure, or decrease the percentage of volatiles in the compound. In certain resins, complete cure and ultimate mechanical properties are attained only by exposure of the cured resin to higher temperatures than those of curing.

pot life The length of time that a catalyzed thermosetting resin system retains a viscosity low enough to be used in processing. Also called working life.

prepreg Either ready-to-mold material in sheet form or ready-to-wind material in roving form, which may be cloth, mat, unidirectional fiber, or paper impregnated with resin and stored for use. The resin is partially cured to a B-stage and supplied to the fabricator, who lays up the finished shape and completes the cure with heat and pressure. The two distinct types of prepreg available are (1) commercial prepregs, where the roving is coated with a hot melt or solvent system to produce a specific product to meet specific customer requirements; and (2) wet prepreg, where the basic resin is installed without solvents or preservatives but has limited room-temperature shelf life.

pressure bag molding A process for molding reinforced plastics in which a tailored, flexible bag is placed over the contact lay-up on the mold, sealed, and clamped in place. Fluid pressure, usually provided by compressed air or water, is placed against the bag, and the part is cured.

pultrusion A continuous process for manufacturing composites that have a constant cross-sectional shape. The process consists of pulling a fiber-reinforcing material through a resin impregnation bath and through a shaping die, where the resin is subsequently cured.

Q

quasi-isotropic laminate A laminate approximating isotropy by orientation of plies in several or more directions.

R

ranking Ordering of laminates by strength, stiffness or others.

reaction injection molding (RIM) A process for molding polyurethane, epoxy, and other liquid chemical systems. Mixing of two to four components in the proper chemical ratio is accomplished by a high-pressure impingement-type mixing head, from which the mixed material is delivered into the mold at low pressure, where it reacts (cures).

reinforced plastics Molded, formed filament-wound, tape-wrapped, or shaped plastic parts consisting of resins to which reinforcing fibers, mats, fabrics, and so forth, have been added before the forming operation to provide some strength properties greatly superior to those of the base resin.

resin A solid or pseudosolid organic material, usually of high molecular weight, that exhibits a tendency to flow when subjected to stress. It usually has a softening or melting range, and fractures conchoidally. Most resins are polymers. In reinforced plastics, the material used to bind together the reinforcement material; the matrix. See also polymer.

resin content The amount of resin in a laminate expressed as either a percentage of total weight or total volume.

resin-rich area Localized area filled with resin and lacking reinforcing material.

resin-starved area Localized area of insufficient resin, usually identified by low gloss, dry spots, or fiber showing on the surface.

resin transfer molding (RTM) A process whereby catalyzed resin is transferred or injected into an enclosed mold in which the fiberglass reinforcement has been placed.

roving A number of yarns, strands, tows, or ends collected into a parallel bundle with little or no twist.

S

sandwich constructions Panels composed of a lightweight core material, such as honeycomb, foamed plastic, and so forth, to which two relatively thin, dense, high-strength or high-stiffness faces or skins are adhered.

scantling The size or weight dimensions of the members which make up the structure of the vessel.

secondary bonding The joining together, by the process of adhesive bonding, of two or more already cured composite parts, during which the only chemical or thermal reaction occurring is the curing of the adhesive itself.

secondary structure Secondary structure is considered that which is not involved in primary bending of the hull girder, such as frames, girders, webs and bulkheads that are attached by secondary bonds.

self-extinguishing resin A resin formulation that will burn in the presence of a flame but will extinguish itself within a specified time after the flame is removed.

set The irrecoverable or permanent deformation or creep after complete release of the force producing the deformation.

set up To harden, as in curing of a polymer resin.

S-glass A magnesium aluminosilicate composition that is especially designed to provide very high tensile strength glass filaments. S-glass and S-2 glass fibers have the same glass composition but different finishes (coatings). S-glass is made to more demanding specifications, and S-2 is considered the commercial grade.

shear An action or stress resulting from applied forces that causes or tends to cause two contiguous parts of a body to slide relative to each other in a direction parallel to their plane of contact. In interlaminar shear, the plane of contact is composed primarily of resin.

shell The watertight boundary of a vessel's hull.

skin Generally, a term used to describe all of the hull shell. For sandwich construction, there is an inner and outer skin which together are thinner than the single-skin laminate that they replace.

skin coat A special layer of resin applied just under the gel coat to prevent blistering. It is sometimes applied with a layer of mat or light cloth.

shear modulus The ratio of shearing stress to shearing strain within the proportional limit of the material.

shear strain The tangent of the angular change, caused by a force between two lines originally perpendicular to each other through a point in a body. Also called angular strain.

shear strength The maximum shear stress that a material is capable of sustaining. Shear strength is calculated from the maximum load during a shear or torsion test and is based on the original cross-sectional area of the specimen.

shear stress The component of stress tangent to the plane on which the forces act.

sheet molding compound (SMC) A composite of fibers, usually a polyester resin, and pigments, fillers, and other additives that have been compounded and processed into sheet form to facilitate handling in the molding operation.

shelf life The length of time a material, substance, product, or reagent can be stored under specified environmental conditions and continue to meet all applicable specification requirements and/or remain suitable for its intended function.

short beam shear (SBS) A flexural test of a specimen having a low test span-to-thickness ratio (for example, 4:1), such that failure is primarily in shear.

size Any treatment consisting of starch, gelatin, oil, wax, or other suitable ingredient applied to yarn or fibers at the time of formation to protect the surface and aid the process of handling and fabrication or to control the fiber characteristics. The treatment contains ingredients that provide surface lubricity and binding action, but unlike a finish, contains no coupling agent. Before final fabrication into a composite, the size is usually removed by heat cleaning, and a finish is applied.

skin The relatively dense material that may form the surface of a cellular plastic or of a sandwich.

S-N diagram A plot of stress (S) against the number of cycles to failure (N) in fatigue testing. A log scale is normally used for N. For S, a linear scale is often used, but sometimes a log scale is used here, too. Also, a representation of the number of alternating stress cycles a material can sustain without failure at various maximum stresses.

specific gravity The density (mass per unit volume) of any material divided by that of water at a standard temperature.

spray-up Technique in which a spray gun is used as an applicator tool. In reinforced plastics, for example, fibrous glass and resin can be simultaneously deposited in a mold. In essence, roving is fed through a chopper and ejected into a resin stream that is directed at the mold by either of two spray systems. In foamed plastics, fast-reacting urethane foams or epoxy foams are fed in liquid streams to the gun and sprayed on the surface. On contact, the liquid starts to foam.

spun roving A heavy, low-cost glass fiber strand consisting of filaments that are continuous but doubled back on each other.

starved area An area in a plastic part which has an insufficient amount of resin to wet out the reinforcement completely. This condition may be due to improper wetting or impregnation or excessive molding pressure.

storage life The period of time during which a liquid resin, packaged adhesive, or prepreg can be stored under specified temperature conditions and remain suitable for use. Also called shelf life.

strain Elastic deformation due to stress. Measured as the change in length per unit of length in a given direction, and expressed in percentage or in./in.

stress The internal force per unit area that resists a change in size or shape of a body. Expressed in force per unit area.

stress concentration On a macromechanical level, the magnification of the level of an applied stress in the region of a notch, void, hole, or inclusion.

stress corrosion Preferential attack of areas under stress in a corrosive environment, where such an environment alone would not have caused corrosion.

stress cracking The failure of a material by cracking or crazing some time after it has been placed under load. Time-to-failure may range from minutes to years. Causes include molded-in stresses, post fabrication shrinkage or warpage, and hostile environment.

stress-strain curve Simultaneous readings of load and deformation, converted to stress and strain, plotted as ordinates and abscissae, respectively, to obtain a stress-strain diagram.

structural adhesive Adhesive used for transferring required loads between adherends exposed to service environments typical for the structure involved.

surfacing mat A very thin mat, usually 7 to 20 mils thick, of highly filamentized fiberglass, used primarily to produce a smooth surface on a reinforced plastic laminate, or for precise machining or grinding.

symmetrical laminate A composite laminate in which the sequence of plies below the laminate midplane is a mirror image of the stacking sequence above the midplane.

T

tack Stickiness of a prepreg; an important handling characteristic.

tape A composite ribbon consisting of continuous or discontinuous fibers that are aligned along the tape axis parallel to each other and bonded together by a continuous matrix phase.

tensile strength The maximum load or force per unit cross-sectional area, within the gage length, of the specimen. The pulling stress required to break a given specimen.

tensile stress The normal stress caused by forces directed away from the plane on which they act.

thermoforming Forming a thermoplastic material after heating it to the point where it is hot enough to be formed without cracking or breaking reinforcing fibers.

thermoplastic polyesters A class of thermoplastic polymers in which the repeating units are joined by ester groups. The two important types are (1) polyethylene terphthalate (PET), which is widely used as film, fiber, and soda bottles; and (2) polybutylene terephthalate (PBT), primarily a molding compound.

thermoset A plastic that, when cured by application of heat or chemical means, changes into a substantially infusible and insoluble material.

thermosetting polyesters A class of resins produced by dissolving unsaturated, generally linear, alkyd resins in a vinyl-type active monomer such as styrene, methyl styrene, or diallyl phthalate. Cure is effected through vinyl polymerization using peroxide catalysts and promoters or heat to accelerate the reaction. The two important commercial types are (1) liquid resins that are cross-linked with styrene and used either as impregnants for glass or carbon fiber reinforcements in laminates, filament-wound structures, and other built-up constructions, or as binders for chopped-fiber reinforcements in molding compounds, such as sheet molding compound (SMC), bulk molding compound (BMC), and thick molding compound (TMC); and (2) liquid or solid resins cross-linked with other esters in chopped-fiber and mineral-filled molding compounds, for example, alkyd and diallyl phthalate.

thixotropic (thixotropy) Concerning materials that are gel-like at rest but fluid when agitated. Having high static shear strength and low dynamic shear strength at the same time. To lose viscosity under stress.

tooling resin Resins that have applications as tooling aids, coreboxes, prototypes, hammer forms, stretch forms, foundry patterns, and so forth. Epoxy and silicone are common examples.

torsion Twisting stress

torsional stress The shear stress on a transverse cross section caused by a twisting action.

toughness A property of a material for absorbing work. The actual work per unit volume or unit mass of material that is required to rupture it. Toughness is proportional to the area under the load-elongation curve from the origin to the breaking point.

tow An untwisted bundle of continuous filaments. Commonly used in referring to manmade fibers, particularly carbon and graphite, but also glass and aramid. A tow designated as 140K has 140,000 filaments.

tracer A fiber, tow, or yarn added to a prepreg for verifying fiber alignment and, in the case of woven materials, for distinguishing warp fibers from fill fibers.

transfer molding Method of molding thermosetting materials in which the plastic is first softened by heat and pressure in a transfer chamber and then forced by high pressure through suitable sprues, runners, and gates into the closed mold for final shaping and curing.

transition temperature The temperature at which the properties of a material change. Depending on the material, the transition change may or may not be reversible.

U

ultimate tensile strength The ultimate or final (highest) stress sustained by a specimen in a tension test. Rupture and ultimate stress may or may not be the same.

ultrasonic testing A nondestructive test applied to materials for the purpose of locating internal flaws or structural discontinuities by the use of high-frequency reflection or attenuation (ultrasonic beam).

uniaxial load A condition whereby a material is stressed in only one direction along the axis or centerline of component parts.

unidirectional fibers Fiber reinforcement arranged primarily in one direction to achieve maximum strength in that direction.

urethane plastics Plastics based on resins made by condensation of organic isocyanates with compounds or resins that contain hydroxyl groups. The resin is furnished as two component liquid monomers or prepolymers that are mixed in the field immediately before application. A great variety of materials are available, depending upon the monomers used in the prepolymers, polyols, and the type of diisocyanate employed. Extremely abrasion and impact resistant. See also polyurethane.

V

vacuum bag molding A process in which a sheet of flexible transparent material plus bleeder cloth and release film are placed over the lay-up on the mold and sealed at the edges. A vacuum is applied between the sheet and the lay-up. The entrapped air is mechanically worked out of the lay-up and removed by the vacuum, and the part is cured with temperature, pressure, and time. Also called bag molding.

veil An ultrathin mat similar to a surface mat, often composed of organic fibers as well as glass fibers.

vinyl esters A class of thermosetting resins containing esters of acrylic and/or methacrylic acids, many of which have been made from epoxy resin. Cure is accomplished as with unsaturated polyesters by copolymerization with other vinyl monomers, such as styrene.

viscosity The property of resistance to flow exhibited within the body of a material, expressed in terms of relationship between applied shearing stress and resulting rate of strain in shear. Viscosity is usually taken to mean Newtonian viscosity, in which case the ratio of shearing stress to the rate of shearing strain is constant. In non-Newtonian behavior, which is the usual case with plastics, the ratio varies with the shearing stress. Such ratios are often called the apparent viscosities at the corresponding shearing stresses. Viscosity is measured in terms of flow in Pa · s (P), with water as the base standard (value of 1.0). The higher the number, the less flow.

void content Volume percentage of voids, usually less than 1% in a properly cured composite. The experimental determination is indirect, that is, calculated from the measured density of a cured laminate and the "theoretical" density of the starting material.

voids Air or gas that has been trapped and cured into a laminate. Porosity is an aggregation of microvoids. Voids are essentially incapable of transmitting structural stresses or nonradiative energy fields.

volatile content The percent of volatiles that are driven off as a vapor from a plastic or an impregnated reinforcement.

volatiles Materials, such as water and alcohol, in a sizing or a resin formulation, that are capable of being driven off as a vapor at room temperature or at a slightly elevated temperature.

W

warp The yarn running lengthwise in a woven fabric. A group of yarns in long lengths and approximately parallel. A change in dimension of a cured laminate from its original molded shape.

water absorption Ratio of the weight of water absorbed by a material to the weight of the dry material.

weathering The exposure of plastics outdoors. Compare with artificial weathering.

weave The particular manner in which a fabric is formed by interlacing yarns. Usually assigned a style number.

weft The transverse threads or fibers in a woven fabric. Those running perpendicular to the warp. Also called fill, filling yarn, or woof.

wet lay-up A method of making a reinforced product by applying the resin system as a liquid when the reinforcement is put in place.

wet-out The condition of an impregnated roving or yarn in which substantially all voids between the sized strands and filaments are filled with resin.

wet strength The strength of an organic matrix composite when the matrix resin is saturated with absorbed moisture, or is at a defined percentage of absorbed moisture less than saturation. (Saturation is an equilibrium condition in which the net rate of absorption under prescribed conditions falls essentially to zero.)

woven roving A heavy glass fiber fabric made by weaving roving or yarn bundles.

Y

yield point The first stress in a material, less than the maximum attainable stress, at which the strain increases at a higher rate than the stress. The point at which permanent deformation of a stressed specimen begins to take place. Only materials that exhibit yielding have a yield point.

yield strength The stress at the yield point. The stress at which a material exhibits a specified limiting deviation from the proportionality of stress to strain. The lowest stress at which a material undergoes plastic deformation. Below this stress, the material is elastic; above it, the material is viscous. Often defined as the stress needed to produce a specified amount of plastic deformation (usually a 0.2% change in length).

Young's modulus The ratio of normal stress to corresponding strain for tensile or compressive stresses less than the proportional limit of the material. See also modulus of elasticity.

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Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
Advanced Textiles Reinforcements																						
C-1200 (NEWF 120)	**0/90 knit**	30.54	2.05	21.69	1.43	11.49	0.74	40.66	2.47	30.65	2.02			59.67	1.98	37.07	0.71			24	41.8%	12.2
C-1600 (NEWF 160)	**0/90 knit**	40.72	2.65	41.00	2.19	11.26	1.31	37.04	2.69	37.08	2.43			47.59	1.39	47.80	1.43			25	58.0%	15.5
C-1800 (NEWF 180)	**0/90 knit**	42.96	2.90	21.18	1.66	10.99	1.18	47.92	3.06	34.08	2.07			64.57	2.07	30.53	1.00			32	51.2%	17.7
C-2300 (NEWF 230)	**0/90 knit**	32.62	2.65	31.43	2.55	9.14	0.88	33.65	2.89	35.70	1.95			57.30	2.18	39.08	1.46			37	54.5%	23.2
CM-1208 (NEWFC 1208)	**0/90 knit w/ mat**	36.76	2.17	21.14	1.66	14.13	1.34	42.40	2.81	29.22	1.71			65.62	2.30	34.61	1.26			37	47.4%	18.9
CM-1215 (NEWFC 1215)	**0/90 knit w/ mat**	23.00	1.86	17.00	1.33			18.00	1.89	16.00	1.60			43.00	1.56	29.00	1.14				34.8%	25.6
CM-1608 (NEWFC 1608)	**0/90 knit w/ mat**	24.75	2.13	27.82	2.07	13.17	1.22	29.93	1.92	23.74	1.90			57.08	1.78	42.40	1.39			44	45.2%	22.5
CM-1615 (NEWFC 1615)	**0/90 knit w/ mat**	22.00	1.77	24.21	1.87	13.63	1.22	21.52	2.05	25.07	1.87			51.17	1.88	47.66	1.67			56	44.3%	29.0
CM-1808 (NEWFC 1808)	**0/90 knit w/ mat**	35.27	2.59	21.21	1.74	13.34	1.19	39.28	2.13	24.39	2.90			63.96	2.07	34.61	1.12			43	46.9%	24.4
CM-1815 (NEWFC 1815)	**0/90 knit w/ mat**	28.48	2.20	21.09	1.82	15.00	1.15	37.00	2.72	23.38	2.06			58.14	2.38	39.13	1.61			57	48.4%	31.2
CM-2308 (NEWFC 2308)	**0/90 knit w/ mat**	29.90	2.37	32.13	2.28	13.86	1.36	38.83	3.13	35.59	2.52			55.55	1.90	50.91	1.42			53	48.8%	29.0
CM-2315 (NEWFC 2315)	**0/90 knit w/ mat**	26.33	1.85	25.73	1.79	13.07	1.18	34.99	2.13	31.76	2.52			51.38	2.03	45.72	1.69			73	48.4%	36.7
CM-3308 (NEWFC 3308)	**0/90 knit w/ mat**	41.19	2.38	48.24	2.52			50.13	2.80	50.23	2.77			66.00	1.80	75.39	1.21			61	55.2%	
CM-3415 (NEWFC 3415)	**0/90 knit w/ mat**	25.46	1.98	33.42	2.01	11.65	1.10	39.99	2.48	38.52	3.16	21.33	1.49	50.08	1.74	53.23	1.65	26.13	1.01	80	50.1%	
CM-3610 (NEWFC 3610)	**0/90 knit w/ mat**	29.86	2.17	41.02	2.27			37.44	3.02	39.34	2.77			49.44	1.84	65.76	2.02			76	51.9%	
X-090 (NEMP 090)	**+/-45 knit**	6.90	0.75	22.65	1.26	23.24	1.68	18.67	0.81	17.80	1.15	41.84	1.74	23.35	0.57	45.33	1.18	48.93	1.56	20	39.0%	9.5
X-120 (NEMP 120)	**+/-45 knit**	6.70	0.80	23.19	1.24	29.38	1.70	15.07	0.80	15.30	1.20	41.26	2.08	19.31	0.67	27.46	1.08	50.66	1.72	27	38.1%	12.4
X-170 (NEMP 170)	**+/-45 knit**	7.61	0.70	23.23	1.12	30.10	1.97	15.82	0.85	16.31	1.11	39.69	1.64	25.16	0.76	45.58	1.15	61.13	1.67	34	46.5%	17.6
X-240 (NEMP 240)	**+/-45 knit**	5.29	1.00	20.35	1.76	26.57	2.08	15.07	0.76	15.44	1.16	42.69	2.03	17.76	0.62	45.62	1.10	61.70	1.88	41	47.8%	24.2
XM-1208 (NEMPC 1208)	**+/-45 knit w/ mat**	13.59	1.30	15.94	1.33	27.04	2.03	21.84	1.04	23.36	1.15	37.44	1.83	31.33	0.92	35.97	1.03	48.37	1.40	39	44.1%	19.2
XM-1215 (NEMPC 1215)	**+/-45 knit w/ mat**	15.68	1.20	16.25	1.02	27.00	2.19	22.05	1.33	22.63	1.17	31.69	2.09	26.67	1.22	29.93	1.32	45.47	1.80	47	46.1%	26.0
XM-1708 (NEMPC 1708)	**+/-45 knit w/ mat**	14.26	1.31	16.22	1.25	31.82	2.05	20.96	1.22	21.42	1.18	38.76	2.04	38.43	0.88	36.41	1.07	60.96	1.65	44	46.7%	24.4
XM-1715 (NEMPC 1715)	**+/-45 knit w/ mat**	16.20	1.36	16.49	1.35	31.49	2.25	20.28	1.25	21.26	1.21	34.53	2.03	34.45	1.18	35.24	1.32	51.19	1.84	51	50.2%	31.1
XM-2408 (NEMPC 2408)	**+/-45 knit w/ mat**	10.58	1.14	20.48	1.34	31.82	2.05	19.30	0.99	20.53	1.16	39.33	2.07	27.08	1.17	42.91	1.37	55.77	1.77	50	50.3%	31.0
XM-2415 (NEMPC 2415)	**+/-45 knit w/ mat**	13.53	1.22	18.92	1.62	24.99	2.19	16.25	0.92	17.09	1.07	25.65	1.39	28.64	1.17	38.66	1.21	45.71	1.54	66	48.7%	37.8
TV-200 (NEWMP 200)	**0, +/-45 knit**	36.40	2.14	11.78	0.98	18.15	1.72	32.80	1.97	20.13	1.09	28.38	1.90	70.21	2.06	28.53	0.59	38.65	1.00	34	48.7%	20.2
TV-230 (NEWMP 230)	**0, +/-45 knit**	30.49	1.67	15.22	0.93	24.64	1.39	29.45	2.48	23.37	1.18	36.70	1.87	63.71	1.85	32.78	0.62	50.71	1.34	39	46.9%	22.8
TV-340 (NEWMP 340)	**0, +/-45 knit**	31.15	1.71	12.95	1.38	21.76	1.59	29.19	2.78	19.96	1.40	28.67	1.68	70.26	2.22	26.63	0.50	47.92	1.17	49	46.8%	33.1
TVM-2008 (NEWMPC 2008)	**0, +/-45 knit w/ mat**	32.15	2.33	11.73	1.16	17.97	1.39	34.07	2.33	22.60	1.24	26.66	2.11	62.39	1.75	27.65	0.66	40.71	1.03	49	47.6%	27.1
TVM-2308 (NEWMPC 2308)	**0, +/-45 knit w/ mat**	29.46	1.73	13.45	0.94	25.16	1.43	33.14	2.05	23.67	1.13	31.97	1.69	66.71	2.02	31.29	0.84	48.34	1.15	49	50.3%	29.5
TVM-2315 (NEWMPC 2315)	**0, +/-45 knit w/ mat**	29.05	2.79	14.10	1.95	21.77	1.65	26.71	1.98	21.19	1.39	25.70	1.80	54.04	1.84	33.66	0.80	51.04	1.32	59	51.9%	
TVM-3408 (NEWMPC 3408)	**0, +/-45 knit w/ mat**	32.41	1.54	13.28	1.80	24.13	1.84	25.61	2.36	18.76	1.50	30.76	2.16	60.42	2.18	29.95	0.69	46.69	1.38	60	53.5%	40.2
TVM-3415 (NEWMPC 3415)	**0, +/-45 knit w/ mat**	33.86	2.42	12.33	1.42	23.80	1.51	30.61	1.80	20.19	1.35	29.67	2.63	57.46	1.55	28.23	0.68	40.08	1.03	71	53.8%	46.8
TH-200 (NEFMP 200)	**90, +/-45 knit**	11.60	1.00	34.09	2.23	21.97	1.89	20.08	1.02	41.39	1.80	33.14	1.62	23.85	1.00	54.50	1.81	33.56	1.02	37	47.4%	
TH-230 (NEFMP 230)	**90, +/-45 knit**	8.86	1.00	33.38	2.11	22.48	1.75	19.60	0.90	38.82	1.96	35.37	1.87	21.86	0.66	56.57	1.75	44.81	1.30	44	46.6%	22.8
TH-340 (NEFMP 340)	**90, +/-45 knit**	8.02	1.06	37.62	2.80	20.07	1.90	20.74	1.07	47.04	2.45	34.90	1.89	18.44	0.57	63.53	2.26	43.61	1.45	55	50.6%	33.1
THM-2308 (NEFMPC 2308)	**90, +/-45 knit & mat**	10.85	1.10	29.88	1.83	20.59	1.67	16.12	0.90	30.37	1.50	19.14	1.34	25.63	0.79	51.43	1.82	45.67	1.48	54	46.2%	29.5
THM-3408 (NEFMPC 3408)	**90, +/-45 knit & mat**	8.41	1.31	37.97	2.45	18.24	1.70	17.70	1.06	40.22	2.36	31.75	1.66	16.44	0.77	63.05	1.83	44.28	1.34	71	48.6%	40.2

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd^2
BTI Reinforcements																						
C-1800	**0/90 knit**	28.80	1.90					43.09	2.60					52.00	2.18					33	44.8%	18.0
C-2400	**0/90 knit**	35.00	2.20					37.23	2.80					64.70	2.40					39	49.7%	24.0
CM-1603	**0/90 deg w/ mat**	34.00	2.00					36.00	2.20					56.00	2.10					37	52.0%	
CM-1808	**0/90 deg w/ mat**	29.20	2.00					27.20	1.70					45.00	1.90					48	43.0%	24.8
CM-1810	**0/90 deg w/ mat**	29.10	2.00					31.60	2.60					46.60	1.86					52	42.0%	27.0
CM-1815	**0/90 deg w/ mat**	27.10	2.00					32.80	2.70					42.50	1.90					55	44.0%	31.5
CM-2403	**0/90 deg w/ mat**	32.00	1.90					33.00	2.40					58.00	2.00					45	50.0%	
CM-2408	**0/90 deg w/ mat**	30.10	1.90					30.30	1.80					51.50	2.00					55	46.0%	30.8
CM-2410	**0/90 deg w/ mat**	29.00	1.90					37.00	2.70					50.00	2.00					62	47.0%	33.0
CM-2415	**0/90 deg w/ mat**	36.97	2.25					36.47	2.70					46.00	1.96					70	44.3%	37.5
CM-3205	**0/90 deg w/ mat**	37.00	2.10					36.00	2.20					51.00	2.20					68	52.0%	
CM-3205/7	**0/90 deg w/ mat**	37.00	2.10					36.00	2.20					51.00	2.20					68	52.0%	
CM-3208	**0/90 deg w/ mat**	36.00	2.00					34.88	2.20					49.00	2.10					71	50.0%	
CM-3215	**0/90 deg w/ mat**	36.00	1.95					37.00	2.70					49.00	2.15					81	49.0%	
CM-3610	**0/90 deg w/ mat**	34.75	2.14											54.25	1.60					79	50.0%	
CM-3610UB	**0/90 deg w/ mat**	34.00	1.90	36.00	2.00			36.00	2.60	38.00	2.10			48.00	2.00	50.00	2.20			88	50.0%	
CM-4810	**0/90 deg w/ mat**	38.00	2.00					39.00	2.10					52.00	2.20					95	52.0%	
M-1000	**binderless mat**	19.00	0.97	19.00	0.97	19.00	0.97	22.00	1.40	22.00	1.40	22.00	1.40	28.00	1.40	28.00	1.40	28.00	1.40	31	26.0%	
M-1500	**binderless mat**	18.70	0.98	18.70	0.98	18.70	0.98	26.00	1.06	26.00	1.06	26.00	1.06	30.80	1.01	30.80	1.01	30.80	1.01	41	30.0%	
M-1500/7	**binderless mat**	18.70	0.98	18.70	0.98	18.70	0.98	26.00	1.06	26.00	1.06	26.00	1.06	30.80	1.01	30.80	1.01	30.80	1.01	41	30.0%	
M-2000	**binderless mat**	19.00	0.98	19.00	0.98	19.00	0.98	24.00	1.20	24.00	1.20	24.00	1.20	30.00	1.40	30.00	1.40	30.00	1.40	52	29.0%	
M-3000	**binderless mat**	17.00	0.96	17.00	0.96	17.00	0.96	23.00	1.10	23.00	1.10	23.00	1.10	29.00	1.30	29.00	1.30	29.00	1.30	75	28.0%	
THM-2210	**horizontal triaxial w/ mat**			29.20	1.90	32.00	2.10			33.10	2.20	36.30	2.60			48.20	1.90	48.90	2.20	53	49.0%	
TV-2500	**vertical triaxial**	34.00	2.20			31.00	2.10	38.10	2.50			36.30	2.40	62.00	2.40			57.00	2.20	35	54.0%	
TV-3400	**vertical triaxial**	35.00	2.20			33.20	2.20	37.20	2.80			36.10	2.80	64.70	2.40			54.10	2.25	51	50.0%	34.0
TVM-3408	**vertical triaxial w/ mat**	33.20	2.25			31.00	2.10	38.10	2.60			36.30	2.60	56.00	2.40			51.00	2.20	68	52.0%	40.8
U-0901	**warp unidirectional**	32.00	2.10					34.00	2.30					57.00	2.10					19	54.0%	
U-1601	**warp unidirectional**	36.00	2.00					38.20	1.90					47.00	2.10					31	52.0%	
U-1801	**warp unidirectional**	38.00	2.00					39.00	2.00					45.00	2.10					35	50.0%	
UM-1608	**warp unidirectional w/ mat**	31.00	1.85					33.20	1.90					45.00	1.90					45	47.0%	
W-16	**weft unidirectional**			38.00	2.10					40.20	2.20					51.00	2.20			27	54.0%	
X-1500	**+/- 45 deg**					33.00	1.85					37.00	2.30					58.00	2.10	26	55.0%	
X-1800	**+/- 45 deg**					32.00	1.90					36.00	2.60					60.80	2.10	31	55.0%	
X-2400	**+/- 45 deg**	7.15				35.50	1.70	15.80	0.56			26.10	2.80					60.00	2.40	36	44.8%	24.0
X-2800	**+/- 45 deg**	8.00				38.50	1.80	18.00	0.60			28.00	2.80					63.00	2.40	41	50.0%	
XM-1305	**+/- 45 deg w/ mat**					35.40	2.00					38.00	2.40					56.80	2.20	26	54.0%	
XM-1308	**+/- 45 deg w/ mat**					31.80	2.00					33.20	2.20					51.00	2.10	29	52.0%	
XM-1708	**+/- 45 deg w/ mat**	13.60	1.50			33.20	2.20	23.40	2.10			36.10	3.16	28.30	1.50			54.10	2.25	48	51.4%	
XM-1808	**+/- 45 deg w/ mat**	13.60	1.50			33.20	2.20	23.40	2.10			36.10	3.16	28.30	1.50			54.10	2.25	48	51.4%	24.8
XM-1808b	**+/- 45 deg w/ mat**	13.60	1.50			33.20	2.20	23.40	2.10			36.10	3.16	28.30	1.50			54.10	2.25	48	51.4%	
XM-2408	**+/- 45 deg w/ mat**	14.20	1.55			34.20	2.20	33.20	2.20			38.00	3.25	32.20	1.50			58.10	2.40	56	55.0%	30.8
XM-2415	**+/- 45 deg w/ mat**	11.50	1.50			27.70	2.10	39.80	3.10			42.60	3.70	29.10	1.50			52.30	2.30	71	53.5%	37.5

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
Owens Corning Knytex Reinforcements																						
1.5 oz chopped mat	**random mat**	12.50	1.10					22.70	1.04					23.80	0.97					46	30.0%	
A 060	**woven warp unidirectional**	70.60	2.60					39.90	2.20					90.60	2.00					10	50.0%	6.1
A 130 Uni	**woven warp unidirectional**	62.40	3.27					44.80	3.55					82.70	2.46					24	50.0%	13.1
A 260 Uni	**woven warp unidirectional**	73.70	3.51					44.10	2.80					109.30	3.61					24	50.0%	25.7
A 260-45 H.M.	**woven warp unidirectional, high modulus**	114.63	5.33																	30	64.4%	25.6
A 260 HBF	**woven warp unidirectional**	106.54	5.06					72.14	4.99					135.48	4.61					31		25.6
A 260 HBF 1587	**woven warp unidirectional**	98.03	4.67																	30	66.5%	25.6
A 260 HBF XP9587	**woven warp unidirectional**	99.86	4.96																	28	66.1%	25.6
A 260 Eng Yarn	**woven warp unidirectional**	113.55	4.96																	32		25.6
A 260 Eng Yarn	**woven warp unidirectional**	101.08	5.20																	30	63.2%	25.6
Biply 2415 G	**woven roving plus mat**	41.19	2.07	35.81	2.01			33.43	2.28	35.29	2.28			55.98	2.21	55.47	2.31			61	50.4%	37.7
CM 1701 Uni/Mat	**warp unidirectional & mat**	74.70	4.20					54.70	3.39					102.60	2.96					30	50.0%	17.3
CM 2415 Uni/Mat	**warp unidirectional & mat**	61.40	2.98					44.50	2.28					73.70	2.35					65	50.0%	
CM3205	**warp unidirectional & mat**	47.11	2.21					49.95	2.49					68.36	1.70					58	59.0%	
CM3610	**warp unidirectional & mat**	52.68	3.07					50.39	2.74					91.39	3.05					55	40.5%	
KA060	**Kevlar® warp unidirectional**	96.10	2.74					30.20	2.94					83.70	1.90					13	50.0%	6.3
D155	**stichbonded weft unidirectional**			60.40	3.73					48.30	4.00					75.40	3.38			27	50.0%	15.5
D240	**stichbonded weft unidirectional**			75.80	3.32					37.90	2.66					88.80	3.05			42	50.0%	24.4
D105	**stichbonded weft unidirectional**			71.10	3.56					33.60	3.26					93.80	2.51			18	50.0%	
CD 185 0/90	**biaxial 0/90**	39.00	1.99	46.00	2.47			16.00	2.36	16.00	2.05			69.00	1.98	49.00	1.66			32	55.0%	19.4
CD 230 0/90	**biaxial 0/90**	36.00	2.60					33.00	2.22					70.00	1.93					41	55.0%	23.5
CD 230 0/90	**biaxial 0/90**	41.30	2.39	32.40	2.26			38.80	2.25	35.50	2.18			64.90	2.40	58.10	2.31			41	50.0%	23.5
DB 090 +/-45	**double bias +/-45**					40.40	2.01					39.30	1.94					62.20	2.05	17	50.0%	9.3
DB 090 +/-45	**double bias +/-45**					47.50	2.25					48.70	1.99					76.20	1.90	17	50.0%	9.3
DB 120 +/-45	**double bias +/-45**					44.50	2.13					35.70	1.92					58.70	2.04	21	50.0%	11.6
DB130	**double bias +/-45**	12.38	1.20	21.26	1.59	31.25	2.08							36.03	1.16	51.89	1.60	62.29	2.14	18	46.1%	
DB 170 +/-45	**double bias +/-45**					39.80	2.18					36.60	2.06					69.90	2.00	31	57.1%	17.6
DB 240 +/-45	**double bias +/-45**					44.90	2.42					37.20	2.34	121.37	4.85			72.50	2.15	44	50.0%	24.7

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
Owens Corning Knytex Reinforcements																						
1.5 oz chopped mat	**random mat**	12.50	1.10					22.70	1.04					23.80	0.97					46	30.0%	
A 060	**woven warp unidirectional**	70.60	2.60					39.90	2.20					90.60	2.00					10	50.0%	6.1
DB 240 +/-45	**double bias +/-45**													94.59	4.32					35	53.6%	24.7
DB 240 +/-45	**double bias +/-45**													144.56	5.22					29	65.4%	24.7
DB400	**double bias +/-45, jumbo**					41.34	2.73					44.74	2.84					68.72	2.12	45	62.5%	39.8
DB603	**double bias +/-45, jumbo**					46.93	2.87					51.66	3.06					66.51	2.44	67	62.5%	58.8
DB800	**double bias +/-45, jumbo**					41.11	2.98					42.61	3.38					71.23	2.61	83	69.2%	
DB803	**double bias +/-45, jumbo**					45.44	3.04					51.00	3.57					62.62	2.63	87	66.4%	
DBM 1208 +/-45/M	**double bias +/-45 plus mat**	18.26	1.35	19.56	1.46	40.60	1.95					31.20	1.70	35.29	1.22	44.81	1.41	60.20	1.75	38	45.0%	19.3
DBM 1708 +/-45/M	**double bias +/-45 plus mat**					36.17	2.21					49.07	2.04					68.98	1.97	39	51.5%	25.3
DBM 1708 +/-45/M	**double bias +/-45 plus mat**					36.60	1.94					38.80	2.10					63.40	1.85	50	45.0%	25.3
DBM2408A	**double bias +/-45 plus mat**					33.04	2.15											65.27	1.82	50	53.2%	
XDBM1703	**exp. double bias +/-45 & mat**					19.15	1.37					34.17	1.78					46.89	1.20	56	39.7%	
XDBM1705	**exp. double bias +/-45 & mat**					13.57	1.10					20.02	1.55					34.51	1.04	51	35.4%	
XDBM1708F	**exp. double bias +/-45 & mat**					31.34	1.89					42.38	2.43					61.27	1.79	40	50.1%	
CDB 200 0/+/-45	**warp triaxial**	45.20	2.23			24.30	1.99	36.80	2.16			33.60	1.89	73.20	2.47			43.50	1.98	39	50.0%	22.4
CDB 340 0/+/-45	**warp triaxial**	48.30	2.42			25.50	1.85	40.30	2.22			25.00	1.97	71.50	2.35			34.70	1.88	55	50.0%	31.4
CDB 340B 0/+/-45	**warp triaxial, promat stich**	36.50	2.45			22.50	1.86	33.20	2.28			29.10	1.75	71.20	2.10			35.60	1.72	59	50.0%	33.5
CDM 1808 0/90/M	**promat (0/90 plus mat)**	37.20	2.10	30.20	1.83			30.20	1.83	28.30	1.45			61.00	2.30	49.20	1.93			54	45.0%	27.0
CDM 1808 B	**promat (0/90 plus mat)**	42.90	2.50					59.74	2.58					75.49	2.58					47	55.2%	29.2
CDM 1815 0/90/M	**promat (0/90 plus mat)**	34.30	2.06	27.60	1.71			28.40	1.74	27.20	1.65			55.90	1.70	53.20	1.45			69	45.0%	32.9
CDM 1815B	**promat (0/90 plus mat)**	40.59	2.52					54.69	2.33					69.20	2.40					50	55.8%	35.1
CDM 2408 0/90/M	**promat (0/90 plus mat)**	35.60	2.12	31.20	1.92			35.70	2.03	34.70	1.87			72.00	2.44	61.20	2.01			69	45.0%	33.1
CDM 2408A	**promat (0/90 plus mat)**	49.08	2.74					63.81	2.08					89.37	2.77					48	56.5%	34.1
CDM 2410 0/90/M	**promat (0/90 plus mat)**	37.20	2.21	35.20	1.91			30.20	1.87	28.40	1.65			61.60	2.12	50.10	1.88			70	45.0%	34.5
CDM 2415 0/90/M	**promat (0/90 plus mat)**	35.20	2.06	31.10	1.97			31.30	1.97	27.20	1.80			58.60	1.95	58.40	1.85			83	45.0%	39.0
CDM 2415	**promat (0/90 plus mat)**	47.74	2.49	49.25	2.40			49.66	2.68	48.48	2.62			72.07	2.06	77.55	2.31			56	54.9%	
CDM 2415A	**promat (0/90 plus mat)**	33.46	2.21	30.03	1.95			70.48	2.49					73.25	2.36	55.32	1.74			59	54.6%	39.6
CDM 3208	**promat (0/90 plus mat)**	44.60	2.47					65.95	2.82					84.53	2.57					55	60.2%	40.0
CDM 3610	**promat (0/90 plus mat)**	52.84	2.88					52.23	3.15					93.29	2.38					56	38.2%	
CDM 3610 ST	**promat (0/90 plus mat)**	51.54	2.74					47.21	3.24					90.66	2.31					55	39.6%	

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd^2
Owens Corning Knytex Reinforcements																						
1.5 oz chopped mat	**random mat**	12.50	1.10					22.70	1.04					23.80	0.97					46	30.0%	
A 060	**woven warp unidirectional**	70.60	2.60					39.90	2.20					90.60	2.00					10	50.0%	6.1
CDM 4408	**promat (0/90 plus mat)**	46.00	2.45	42.59	2.75			50.05	2.45	58.07	2.74			63.78	2.33	84.00	3.05				54.6%	
XCDM 2315	**exp promat (0/90 plus mat)**	36.54	2.10	36.04	2.10									71.18	2.01	58.72	1.77			60	54.9%	
DDB222	**weft triaxial**	38.40	2.55			22.40	1.41	33.20	2.04			28.60	1.88	57.50	2.10			42.10	1.77	39	50.0%	22.1
DDB340	**weft triaxial**	48.00	2.45	71.93	2.88	23.50	1.33	33.90	2.23			27.70	1.93	65.60	2.23	79.56	2.80	49.10	1.83	59	50.0%	33.8
XDDBM2208	**exp weft triaxial w/ mat**			38.32	2.20	19.65	1.59													51	48.9%	
XDDM2710	**exp stichbonded weft triaxial w/ mat**			43.68	2.32	22.04	1.58									71.43	2.39	43.06	1.54	55	53.6%	
XDDB222	**exp stichbonded weft triaxial**	12.48	1.16	54.64	2.69									25.32	1.28	78.41	2.59			30		
XDDB340	**exp stichbonded weft triaxial**	12.02	1.13	71.08	3.20									25.58	1.31	95.26	3.20			39		
GDB 095 +/-45 carbon	**double bias +/-45 carbon**					67.00	4.98					52.00	4.55					90.00	2.77		50.0%	9.8
GDB 095 +/-45 carbon	**double bias +/-45 carbon**					90.20	4.59					58.50	2.97					86.50	2.14	20	50.0%	9.8
GDB 120 +/-45 carbon	**double bias +/-45 carbon**					67.00	6.19					28.00	5.84					103.00	3.39		50.0%	12.3
GDB 120 +/-45 carbon	**double bias +/-45 carbon**					76.60	5.28					44.50	2.39					80.40	2.23	25	50.0%	12.3
GDB 200 +/-45 carbon	**double bias +/-45 carbon**					58.00	6.94					18.00	5.57					78.00	3.04		50.0%	19.8
GDB 200 +/-45 carbon	**double bias +/-45 carbon**					72.90	5.66					41.20	3.55					95.60	2.65	40	50.0%	19.8
KDB 170 +/-45 Kevlar	**double bias +/-45 Kevlar®**					51.00	3.23					12.00						34.00			50.0%	15.9
17MPX						37.60	2.20					32.50	1.71					59.80	1.72	31	50.0%	
XH120		59.20	3.60					30.00	2.53					45.10	1.65					56	50.0%	
XH120						17.50	1.43					17.40	1.78					22.00	1.20	56	50.0%	
CDDB310	**quadraxial**	34.02	1.81	31.56	1.93			36.79	1.87	31.12	1.86			57.26	1.49	50.14	1.39			46	55.0%	
CDB 340 0/+/-45	**warp triaxial**	48.00	2.61					34.00	2.27					67.00	2.06						55.0%	31.4
CDM 2410 0/90/M	**promat**	37.00	2.31					27.00	1.87					54.00	1.41						45.0%	34.5
GA 045 Uni carbon	**woven warp unidirectional, carbon**	97.00	9.34					76.00	11.75					195.00	8.98						55.0%	4.6
GA 080 Uni carbon	**woven warp unidirectional, carbon**	244.40	18.30											135.80	10.90						48.0%	
GA 090 Uni carbon	**woven warp unidirectional, carbon**	232.90	18.90					45.71	11.49					173.60	14.50					15	58.0%	9.4
GA 130 Uni carbon	**woven warp unidirectional, carbon**	234.60	18.20					45.94	12.73					150.90	12.20					18	64.0%	
KBM 1308A	**woven Kevlar®/glass hybrid plus mat**	48.23	2.48											46.89	2.20					30		

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
Owens Corning Knytex Reinforcements																						
1.5 oz chopped mat	**random mat**	12.50	1.10					22.70	1.04					23.80	0.97					46	30.0%	
A 060	**woven warp unidirectional**	70.60	2.60					39.90	2.20					90.60	2.00					10	50.0%	6.1
Kevlar/Glass Hybrid		42.45	2.28	37.38	2.15									58.24	2.14					27		
KDB 110 +/-45 Kevlar	**double bias, Kevlar®**					56.00	3.63					15.00	1.32					49.00	1.11		45.0%	10.4
KDB 110 +/-45 Kevlar	**double bias, Kevlar®**					73.70	3.00					19.90	1.30					65.70	1.96	23	50.0%	10.4
KB 203 WR E-glass/Kevlar	**woven Kevlar®/glass hybrid**	66.00	5.48					21.00	3.47					51.00	2.42						45.0%	20.8
SDB 120 S-glass	**double bias, S-glass**	63.00	3.03					45.00	2.90					70.60	1.88						55.0%	11.4
SDB 120 S-glass	**double bias, S-glass**	60.00	2.35					46.20	2.10					78.30	2.23					21	50.0%	17.2
B238	**starch oil woven roving**	31.60	1.91	28.20	1.80			28.50	1.80	26.70	1.76			48.80	1.85	44.30	1.78			57	40.0%	
B238+.75 oz mat	**starch oil woven roving w/ mat**	27.50	1.78	25.10	1.68			26.80	1.79	24.50	1.73			42.10	1.80	39.70	1.71			86	35.0%	
Spectra 900	**Spectra**	63.70	2.85	54.10	2.65			18.80	2.04	16.60	1.88			48.40	1.80	44.20	1.72			17	50.0%	
K49/13 Kevlar	**Kevlar® 49**	51.80	2.89	48.90	2.79			19.70	2.35	17.50	2.10			42.20	1.50	39.10	1.43			27	45.0%	

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
DuPont Kevlar Reinforcements																						
Kevlar 49 243	unidirectional	80.10	5.43											34.60	3.84							6.7
Kevlar 49 243	unidirectional	90.80	6.60											50.40	4.85							6.7
Kevlar 49 281	woven cloth	59.70	3.23											32.10	2.54							5.0
Kevlar 49 281	woven cloth	60.60	3.74											36.60	3.16							5.0
Kevlar 49 285	woven cloth	49.00	2.75											31.50	2.37							5.0
Kevlar 49 285	woven cloth	59.00	3.22											41.00	2.81							5.0
Kevlar 49 328	woven cloth	63.60	3.10											23.50	2.59							6.3
Kevlar 49 500	woven cloth	51.70	2.98											37.80	2.06							5.0
Kevlar 49 500	woven cloth	55.20	3.73											50.60	2.83							5.0
Kevlar 49 1050	woven roving	44.60	3.13											26.90	2.01							10.5
Kevlar 49 1050	woven roving	59.70	2.98											35.40	2.64							10.5
Kevlar 49 1033	woven roving	50.70	3.55											22.50	2.22							15.0
Kevlar 49 1033	woven roving	52.40	3.42											34.40	2.67							15.0
Kevlar 49 1350	woven roving	65.00	7.70											29.30	3.15							13.5
Kevlar 49 118	woven roving	88.80												61.00	6.10							8.0
Kevlar 49/E-glass KBM 1308	woven/mat	34.80	1.79	33.64	1.83			24.65	2.33	25.38	1.94			37.57	1.44	37.13	1.46					18.6
Kevlar 49/E-glass KBM 2808	woven/mat	39.01	2.12	33.79	2.00			22.19	2.19	22.19	2.39			43.51	1.75	36.69	1.76					33.1
Kevlar 49/E-glass C77K/235		39.01	2.12	33.79	2.00									43.51	1.70	36.69	1.76				45.0%	33.2
Anchor Reinforcements																						
Ancaref C160 carbon, 12K	unidirectional	127.00	12.00					90.00	9.00											4	50.0%	4.7
Ancaref C160 carbon, 12K	unidirectional	250.00	21.00					160.00	20.00											3	70.0%	4.7
Ancaref C320 carbon, 12K	unidirectional	125.00	12.00					90.00	9.00											21		9.5
Ancaref C440 carbon, 12K	unidirectional	89.00	5.30					31.00	3.80											14		6.1
Ancaref S275 S-2 glass, O-C	unidirectional	129.00	5.50					62.00												9	60.0%	8.1
Ancaref S275 S-2 glass, O-C	unidirectional	298.00	7.50					119.00	7.80											7	75.0%	8.1
Ancaref S160 S-2 glass, O-C	unidirectional	128.00	5.50					62.00	7.70											7		4.8
Ancaref G230 E-glass	unidirectional	76.00	4.30					79.00	3.10											14		9.5
Unidirectionals																						
High-strength, uni tape carbon	unidirectional	180.00	21.00	8.00	1.70	23.20	2.34	180.00	21.00	30.00	1.70	23.90	2.34									
High-strength, uni tape carbon	unidirectional	180.00	18.70	4.00	0.87	13.20	1.20	70.00	18.70	12.00	0.87	13.70	1.20									
High-modulus, uni tape carbon	unidirectional	110.00	25.00	4.00	1.70	16.90	2.38	100.00	25.00	20.00	1.70	18.00	2.38									
High-modulus, uni tape carbon	unidirectional	96.00	24.10	3.10	0.85	7.20	1.86	60.00	24.10	8.00	0.85	7.20	1.86									
Intermediate-strength, uni tape carbon	unidirectional	160.00	17.00	7.50	1.70			160.00	17.00	25.00	1.70											
Intermediate-strength, uni tape carbon	unidirectional	144.00	16.00	4.00	1.00			65.00	16.00	15.00	1.00											
Unidirectional tape Kevlar	unidirectional	170.00	10.10	4.00	0.80			40.00	10.10	20.00	0.80											

Reinforcement Description	Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd^2
SCRIMP Process Laminates																					
Cert'teed/Seemann 625 WR							43.60						70.60						24	73.0%	24.0
Cert'teed/Seemann 625 WR	57.10						52.00						79.50						24	73.0%	24.0
Hexcell 8HS, Style 7781	56.90	3.40					58.10						83.60						10	66.0%	8.5
FGI/Seemann 3X1, 10 Twill	53.60	3.40					61.70						76.70						10	70.0%	9.6
8HS, 3K XaSg, 1029 carbon	98.00	8.30					37.00						69.70						16		10.9
8HS, 3K, 1029(UC309) carbon							42.10						68.20						16		10.9
5HS, 12K, 1059(AS4W) carbon		7.90					29.50						60.20						22		15.5
Hexcell CD180 stiched biaxial	50.10	3.20					41.50						59.70						26	64.0%	19.4
Chomarat 2 x 2 weave	40.20	2.90					55.00						69.30						31	61.0%	24.0
DF14OO	47.20	3.90	35.00	3.40			39.30		34.70				61.30		46.20				42	66.0%	40.0
G:CI029 hybrid E-glass/carbon	71.10	6.40					39.70						96.50						40		
G:CI059 hybrid E-glass/carbon	64.20	6.10					29.00						99.30						40		
G:K285(60%) hybrid E-glass/Kevlar							23.80						75.40						48		
G:K900(40%) hybrid E-glass/Kevlar							36.70						73.90						33		
G:K900(50%) hybrid E-glass/Kevlar	57.50	3.70					31.80						62.60						38		
G:S985(40%) hybrid E-glass/Spectra	51.50	3.10					35.10						78.50						33		
DuPont 5HS, K49, Kevlar (900)	69.50	4.30					15.80						35.50						17		
Allied-Signal 8HS, S1000, Spectra (985)		2.10					8.50						18.50						10		5.5
Cert'teed/Seemann 625 WR	51.60	3.50					47.80						71.90						24	73.0%	24.0
Cert'teed/Seemann twill, 3X1	51.30	3.10					52.90						79.10						26	71.0%	24.0
Cert'teed/Seemann 625 WR	44.70	3.60					30.80						48.70						24	73.0%	24.0
Cert'teed/Seemann 625 WR	51.50	3.90					32.80						55.00						24	73.0%	24.0
Cert'teed/Seemann 625 WR	48.70	3.90					32.20						58.20						24	73.0%	24.0
5HS, 6K, 1030 carbon	92.00	8.50					57.20						99.20						15		10.2
5HS, 12K, 1059 carbon (AS4W)	89.20	8.30					64.50						100.10						22		15.5
Low-Temperature Cure Prepregs																					
Advanced Comp Grp/LTM21	76.00	4.20					59.90						74.80							77.9%	24.0
Advanced Comp Grp/LTM22	63.50	3.40					48.70						69.30						9	65.9%	8.9
Advanced Comp Grp/LTM22	67.80	3.50					51.20						73.60						9	66.9%	8.9
SP Systems/Ampreg 75	61.80	3.10					60.70						81.60						9	65.5%	8.9
SP Systems/Ampreg 75	66.10	3.30					63.80						90.10						9	62.8%	8.9
DSM Italia/Neoxil	50.10	2.80					68.60						87.20						9	57.0%	8.9
Newport Adhesives/NB-1101	50.60	2.90					57.00						68.50						9	60.3%	8.9
Newport Adhesives/NB-1101	48.30	3.00					62.30						69.60						9	60.3%	8.9
Newport Adhesives/NB-1107	58.30	3.30					59.20						75.20						9	63.3%	8.9
Newport Adhesives/NB-1107	48.20	2.30					48.30						57.80						9	63.3%	8.9
Ciba Composite/M10E	53.60	3.30					52.10						77.10						9	62.8%	8.9
Ciba Composite/M10E	93.50	9.20					44.20						85.80						9		8.9
YLA, Inc./RS-1	51.80	3.10					51.90						70.80						9	64.7%	8.9

Reinforcement Description	Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	ksi	msi	mils	%	oz/yd²
YLA, Inc./RS-1	51.30	3.00					53.60						68.60						9	64.8%	8.9
YLA, Inc./RS-1	55.30	3.00					55.90						71.30						9	63.6%	8.9
3M/SP377	41.90	3.10					56.50						59.70						9	63.1%	8.9
3M/SP377	43.00	3.30					59.40						59.40						9	64.4%	8.9
3M/SP365	35.30						37.50						48.90						16	68.5%	16.1
3M/SP365	47.30						59.20						71.40						16	69.5%	16.1
Fibercote Industries/E-761E	55.30	3.40					63.10						75.90						16	62.4%	16.1
Fibercote Industries/E-761E	58.30	3.50					66.00						78.60						16	62.6%	16.1
Fibercote Industries/P-601	61.30	3.30					64.30						87.50						25	57.0%	18.0
Fibercote Industries/P-601	64.10	3.40					70.20						90.60						25	60.3%	18.0
Fibercote Industries/P-600	54.50	2.90					43.00						66.70						9	62.6%	8.9
Fibercote Industries/P-600	58.70	3.10					50.60						78.70						9	64.7%	8.9
ICI Fiberite/MXB-9420	61.10	2.90					50.40						67.30						9	60.9%	8.9
Fiber Content Study for GLCC																					
Owens-Corning WR	44.50	2.99					45.65	3.31					58.76	2.29					25	52.4%	18.0
ATI NEWF 180 Biaxial	51.92	3.29					51.61	3.55					75.29	2.66					30	47.8%	18.0
Owens-Corning WR	57.58	3.68					46.44	3.57					81.92	2.87					25	61.0%	18.0
ATI NEWF 180 Biaxial	56.38	3.26					61.14	3.54					81.88	2.82					30	53.1%	18.0
Owens-Corning WR	58.40	3.72					46.67	3.64					93.65	3.30					25	66.9%	18.0
ATI NEWF 180 Biaxial	61.06	3.41					55.97	3.56					83.59	2.73					30	61.8%	18.0

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m²
Advanced Textiles Reinforcements																						
C-1200 (NEWF 120)	0/90 knit	211	14.1	150	9.9	79	5.1	280	17.0	211	13.9			411	13.7	256	4.9			0.61	41.8%	412
C-1600 (NEWF 160)	0/90 knit	281	18.3	283	15.1	78	9.0	255	18.5	256	16.8			328	9.6	330	9.8			0.64	58.0%	524
C-1800 (NEWF 180)	0/90 knit	296	20.0	146	11.4	76	8.2	330	21.1	235	14.3			445	14.3	210	6.9			0.81	51.2%	598
C-2300 (NEWF 230)	0/90 knit	225	18.3	217	17.6	63	6.1	232	19.9	246	13.4			395	15.0	269	10.1			0.94	54.5%	784
CM-1208 (NEWFC 1208)	0/90 knit w/ mat	253	14.9	146	11.4	97	9.2	292	19.4	201	11.8			452	15.8	239	8.7			0.94	47.4%	639
CM-1215 (NEWFC 1215)	0/90 knit w/ mat	159	12.8	117	9.2			124	13.0	110	11.1			296	10.8	200	7.9				34.8%	865
CM-1608 (NEWFC 1608)	0/90 knit w/ mat	171	14.7	192	14.3	91	8.4	206	13.2	164	13.1			394	12.3	292	9.6			1.12	45.2%	761
CM-1615 (NEWFC 1615)	0/90 knit w/ mat	152	12.2	167	12.9	94	8.4	148	14.1	173	12.9			353	13.0	329	11.5			1.42	44.3%	980
CM-1808 (NEWFC 1808)	0/90 knit w/ mat	243	17.8	146	12.0	92	8.2	271	14.7	168	20.0			441	14.3	239	7.7			1.09	46.9%	825
CM-1815 (NEWFC 1815)	0/90 knit w/ mat	196	15.2	145	12.6	103	7.9	255	18.8	161	14.2			401	16.4	270	11.1			1.45	48.4%	1055
CM-2308 (NEWFC 2308)	0/90 knit w/ mat	206	16.4	222	15.7	96	9.4	268	21.6	245	17.4			383	13.1	351	9.8			1.35	48.8%	980
CM-2315 (NEWFC 2315)	0/90 knit w/ mat	182	12.8	177	12.4	90	8.1	241	14.7	219	17.4			354	14.0	315	11.6			1.85	48.4%	1240
CM-3308 (NEWFC 3308)	0/90 knit w/ mat	284	16.4	333	17.3			346	19.3	346	19.1			455	12.4	520	8.3			1.55	55.2%	
CM-3415 (NEWFC 3415)	0/90 knit w/ mat	176	13.6	230	13.9	80	7.6	276	17.1	266	21.8	147	10.3	345	12.0	367	11.3	180	6.9	2.03	50.1%	
CM-3610 (NEWFC 3610)	0/90 knit w/ mat	206	15.0	283	15.6			258	20.8	271	19.1			341	12.7	453	13.9			1.93	51.9%	
X-090 (NEMP 090)	+/-45 knit	48	5.2	156	8.7	160	11.6	129	5.6	123	7.9	288	12.0	161	3.9	313	8.1	337	10.8	0.51	39.0%	321
X-120 (NEMP 120)	+/-45 knit	46	5.5	160	8.5	203	11.7	104	5.5	105	8.3	284	14.3	133	4.6	189	7.4	349	11.9	0.69	38.1%	419
X-170 (NEMP 170)	+/-45 knit	52	4.8	160	7.7	208	13.6	109	5.9	112	7.7	274	11.3	173	5.2	314	7.9	421	11.5	0.86	46.5%	595
X-240 (NEMP 240)	+/-45 knit	36	6.9	140	12.1	183	14.3	104	5.2	106	8.0	294	14.0	122	4.3	315	7.6	425	13.0	1.04	47.8%	818
XM-1208 (NEMPC 1208)	+/-45 knit w/ mat	94	9.0	110	9.2	186	14.0	151	7.2	161	7.9	258	12.6	216	6.3	248	7.1	333	9.7	0.99	44.1%	649
XM-1215 (NEMPC 1215)	+/-45 knit w/ mat	108	8.3	112	7.0	186	15.1	152	9.2	156	8.1	219	14.4	184	8.4	206	9.1	314	12.4	1.19	46.1%	879
XM-1708 (NEMPC 1708)	+/-45 knit w/ mat	98	9.0	112	8.6	219	14.1	145	8.4	148	8.1	267	14.1	265	6.1	251	7.4	420	11.4	1.12	46.7%	825
XM-1715 (NEMPC 1715)	+/-45 knit w/ mat	112	9.4	114	9.3	217	15.5	140	8.6	147	8.3	238	14.0	238	8.1	243	9.1	353	12.7	1.30	50.2%	1051
XM-2408 (NEMPC 2408)	+/-45 knit w/ mat	73	7.9	141	9.2	219	14.1	133	6.8	142	8.0	271	14.3	187	8.1	296	9.4	385	12.2	1.27	50.3%	1048
XM-2415 (NEMPC 2415)	+/-45 knit w/ mat	93	8.4	130	11.2	172	15.1	112	6.3	118	7.4	177	9.6	197	8.1	267	8.3	315	10.6	1.68	48.7%	1278
TV-200 (NEWMP 200)	0, +/-45 knit	251	14.8	81	6.8	125	11.9	226	13.6	139	7.5	196	13.1	484	14.2	197	4.1	266	6.9	0.86	48.7%	683
TV-230 (NEWMP 230)	0, +/-45 knit	210	11.5	105	6.4	170	9.6	203	17.1	161	8.1	253	12.9	439	12.8	226	4.3	350	9.2	0.99	46.9%	771
TV-340 (NEWMP 340)	0, +/-45 knit	215	11.8	89	9.5	150	11.0	201	19.2	138	9.7	198	11.6	484	15.3	184	3.4	330	8.1	1.24	46.8%	1119
TVM-2008 (NEWMPC 2008)	0, +/-45 knit w/ mat	222	16.1	81	8.0	124	9.6	235	16.1	156	8.5	184	14.5	430	12.1	191	4.6	281	7.1	1.24	47.6%	916
TVM-2308 (NEWMPC 2308)	0, +/-45 knit w/ mat	203	11.9	93	6.5	173	9.9	229	14.1	163	7.8	220	11.7	460	13.9	216	5.8	333	7.9	1.24	50.3%	997
TVM-2315 (NEWMPC 2315)	0, +/-45 knit w/ mat	200	19.2	97	13.4	150	11.4	184	13.7	146	9.6	177	12.4	373	12.7	232	5.5	352	9.1	1.50	51.9%	
TVM-3408 (NEWMPC 3408)	0, +/-45 knit w/ mat	223	10.6	92	12.4	166	12.7	177	16.3	129	10.3	212	14.9	417	15.0	207	4.8	322	9.5	1.52	53.5%	1359
TVM-3415 (NEWMPC 3415)	0, +/-45 knit w/ mat	233	16.7	85	9.8	164	10.4	211	12.4	139	9.3	205	18.1	396	10.7	195	4.7	276	7.1	1.80	53.8%	1582
TH-200 (NEFMP 200)	90, +/-45 knit	80	6.9	235	15.4	151	13.0	138	7.0	285	12.4	229	11.2	164	6.9	376	12.5	231	7.0	0.94	47.4%	
TH-230 (NEFMP 230)	90, +/-45 knit	61	6.9	230	14.5	155	12.1	135	6.2	268	13.5	244	12.9	151	4.6	390	12.1	309	9.0	1.12	46.6%	771
TH-340 (NEFMP 340)	90, +/-45 knit	55	7.3	259	19.3	138	13.1	143	7.4	324	16.9	241	13.0	127	3.9	438	15.6	301	10.0	1.40	50.6%	1119
THM-2308 (NEFMPC 2308)	90, +/-45 knit & mat	75	7.6	206	12.6	142	11.5	111	6.2	209	10.3	132	9.2	177	5.4	355	12.5	315	10.2	1.37	46.2%	997
THM-3408 (NEFMPC 3408)	90, +/-45 knit & mat	58	9.0	262	16.9	126	11.7	122	7.3	277	16.3	219	11.4	113	5.3	435	12.6	305	9.2	1.80	48.6%	1359

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m^2
BTI Reinforcements																						
C-1800	**0/90 knit**	199	13.1					297	17.9					359	15.0					0.84	44.8%	608
C-2400	**0/90 knit**	241	15.2					257	19.3					446	16.5					0.99	49.7%	811
CM-1603	**0/90 deg w/ mat**	234	13.8					248	15.2					386	14.5					0.94	52.0%	
CM-1808	**0/90 deg w/ mat**	201	13.8					188	11.7					310	13.1					1.22	43.0%	838
CM-1810	**0/90 deg w/ mat**	201	13.8					218	17.9					321	12.8					1.32	42.0%	913
CM-1815	**0/90 deg w/ mat**	187	13.8					226	18.6					293	13.1					1.40	44.0%	1065
CM-2403	**0/90 deg w/ mat**	221	13.1					228	16.5					400	13.8					1.14	50.0%	
CM-2408	**0/90 deg w/ mat**	208	13.1					209	12.4					355	13.8					1.40	46.0%	1041
CM-2410	**0/90 deg w/ mat**	200	13.1					255	18.6					345	13.8					1.57	47.0%	1115
CM-2415	**0/90 deg w/ mat**	255	15.5					251	18.6					317	13.5					1.78	44.3%	1268
CM-3205	**0/90 deg w/ mat**	255	14.5					248	15.2					352	15.2					1.73	52.0%	
CM-3205/7	**0/90 deg w/ mat**	255	14.5					248	15.2					352	15.2					1.73	52.0%	
CM-3208	**0/90 deg w/ mat**	248	13.8					240	15.2					338	14.5					1.80	50.0%	
CM-3215	**0/90 deg w/ mat**	248	13.4					255	18.6					338	14.8					2.06	49.0%	
CM-3610	**0/90 deg w/ mat**	240	14.8											374	11.0					2.01	50.0%	
CM-3610UB	**0/90 deg w/ mat**	234	13.1	248	13.8			248	17.9	262	14.5			331	13.8	345	15.2			2.24	50.0%	
CM-4810	**0/90 deg w/ mat**	262	13.8					269	14.5					359	15.2					2.41	52.0%	
M-1000	**binderless mat**	131	6.7	131	6.7	131	6.7	152	9.7	152	9.7	152	9.7	193	9.7	193	9.7	193	9.7	0.79	26.0%	
M-1500	**binderless mat**	129	6.8	129	6.8	129	6.8	179	7.3	179	7.3	179	7.3	212	7.0	212	7.0	212	7.0	1.04	30.0%	
M-1500/7	**binderless mat**	129	6.8	129	6.8	129	6.8	179	7.3	179	7.3	179	7.3	212	7.0	212	7.0	212	7.0	1.04	30.0%	
M-2000	**binderless mat**	131	6.8	131	6.8	131	6.8	165	8.3	165	8.3	165	8.3	207	9.7	207	9.7	207	9.7	1.32	29.0%	
M-3000	**binderless mat**	117	6.6	117	6.6	117	6.6	159	7.6	159	7.6	159	7.6	200	9.0	200	9.0	200	9.0	1.91	28.0%	
THM-2210	**horizontal triaxial w/ mat**			201	13.1	221	14.5			228	15.2	250	17.9			332	13.1	337	15.2	1.35	49.0%	
TV-2500	**vertical triaxial**	234	15.2			214	14.5	263	17.2			250	16.5	427	16.5			393	15.2	0.89	54.0%	
TV-3400	**vertical triaxial**	241	15.2			229	15.2	256	19.3			249	19.3	446	16.5			373	15.5	1.30	50.0%	1149
TVM-3408	**vertical triaxial w/ mat**	229	15.5			214	14.5	263	17.9			250	17.9	386	16.5			352	15.2	1.73	52.0%	1379
U-0901	**warp unidirectional**	221	14.5					234	15.9					393	14.5					0.48	54.0%	
U-1601	**warp unidirectional**	248	13.8					263	13.1					324	14.5					0.79	52.0%	
U-1801	**warp unidirectional**	262	13.8					269	13.8					310	14.5					0.89	50.0%	
UM-1608	**warp unidirectional w/ mat**	214	12.8					229	13.1					310	13.1					1.14	47.0%	
W-16	**weft unidirectional**			262	14.5					277	15.2					352	15.2			0.69	54.0%	
X-1500	**+/- 45 deg**					228	12.8					255	15.9					400	14.5	0.66	55.0%	
X-1800	**+/- 45 deg**					221	13.1					248	17.9					419	14.5	0.79	55.0%	
X-2400	**+/- 45 deg**	49				245	11.7	109	3.9			180	19.3					414	16.5	0.91	44.8%	811
X-2800	**+/- 45 deg**	55				265	12.4	124	4.1			193	19.3					434	16.5	1.04	50.0%	
XM-1305	**+/- 45 deg w/ mat**					244	13.8					262	16.5					392	15.2	0.66	54.0%	
XM-1308	**+/- 45 deg w/ mat**					219	13.8					229	15.2					352	14.5	0.74	52.0%	
XM-1708	**+/- 45 deg w/ mat**	94	10.3			229	15.2	161	14.5			249	21.8	195	10.3			373	15.5	1.22	51.4%	
XM-1808	**+/- 45 deg w/ mat**	94	10.3			229	15.2	161	14.5			249	21.8	195	10.3			373	15.5	1.22	51.4%	838
XM-1808b	**+/- 45 deg w/ mat**	94	10.3			229	15.2	161	14.5			249	21.8	195	10.3			373	15.5	1.22	51.4%	
XM-2408	**+/- 45 deg w/ mat**	98	10.7			236	15.2	229	15.2			262	22.4	222	10.3			401	16.5	1.42	55.0%	1041
XM-2415	**+/- 45 deg w/ mat**	79	10.3			191	14.5	274	21.4			294	25.5	201	10.3			361	15.9	1.80	53.5%	1268

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m²
Owens Corning Knytex Reinforcements																						
1.5 oz chopped mat	random mat	86	7.6					157	7.2					164	6.7					1.17	30.0%	
A 060	woven warp unidirectional	487	17.9					275	15.2					625	13.8					0.25	50.0%	206
A 130 Uni	woven warp unidirectional	430	22.5					309	24.5					570	17.0					0.61	50.0%	443
A 260 Uni	woven warp unidirectional	508	24.2					304	19.3					754	24.9					0.61	50.0%	869
A 260-45 H.M.	woven warp unidirectional, high modulus	790	36.7																	0.76	64.4%	865
A 260 HBF	woven warp unidirectional	735	34.9					497	34.4					934	31.8					0.79		865
A 260 HBF 1587	woven warp unidirectional	676	32.2																	0.76	66.5%	865
A 260 HBF XP9587	woven warp unidirectional	688	34.2																	0.71	66.1%	865
A 260 Eng Yarn	woven warp unidirectional	783	34.2																	0.81		865
A 260 Eng Yarn	woven warp unidirectional	697	35.9																	0.76	63.2%	865
Biply 2415 G	woven roving plus mat	284	14.3	247	13.9			231	15.7	243	15.7			386	15.2	382	15.9			1.55	50.4%	1274
CM 1701 Uni/Mat	warp unidirectional & mat	515	29.0					377	23.4					707	20.4					0.76	50.0%	585
CM 2415 Uni/Mat	warp unidirectional & mat	423	20.5					307	15.7					508	16.2					1.65	50.0%	
CM3205	warp unidirectional & mat	325	15.3					344	17.1					471	11.7					1.47	59.0%	
CM3610	warp unidirectional & mat	363	21.1					347	18.9					630	21.0					1.40	40.5%	
KA060	Kevlar® warp unidirectional	663	18.9					208	20.3					577	13.1					0.33	50.0%	213
D155	stichbonded weft unidirectional			416	25.7					333	27.6					520	23.3			0.69	50.0%	524
D240	stichbonded weft unidirectional			523	22.9					261	18.3					612	21.0			1.07	50.0%	825
D105	stichbonded weft unidirectional			490	24.5					232	22.5					647	17.3			0.46	50.0%	
CD 185 0/90	biaxial 0/90	269	13.7	317	17.0			110	16.3	110	14.2			476	13.6	338	11.5			0.81	55.0%	656
CD 230 0/90	biaxial 0/90	248	18.0					228	15.3					483	13.3					1.04	55.0%	794
CD 230 0/90	biaxial 0/90	285	16.5	223	15.6			268	15.5	245	15.0			447	16.5	401	15.9			1.04	50.0%	794
DB 090 +/-45	double bias +/-45					279	13.9					271	13.4					429	14.1	0.43	50.0%	314
DB 090 +/-45	double bias +/-45					328	15.5					336	13.7					525	13.1	0.43	50.0%	314
DB 120 +/-45	double bias +/-45					307	14.7					246	13.2					405	14.1	0.53	50.0%	392
DB130	double bias +/-45	85	8.3	147	11.0	215	14.3							248	8.0	358	11.0	429	14.7	0.46	46.1%	
DB 170 +/-45	double bias +/-45					274	15.0					252	14.2					482	13.8	0.79	57.1%	595
DB 240 +/-45	double bias +/-45					310	16.7					256	16.1					500	14.8	1.12	50.0%	835
DB 240 +/-45	double bias +/-45																			0.89	53.6%	835
DB 240 +/-45	double bias +/-45																			0.74	65.4%	835
DB400	double bias +/-45, jumbo					285	18.8					308	19.6					474	14.6	1.14	62.5%	1345
DB603	double bias +/-45, jumbo					324	19.8					356	21.1					459	16.8	1.70	62.5%	1987
DB800	double bias +/-45, jumbo					283	20.6					294	23.3					491	18.0	2.11	69.2%	
DB803	double bias +/-45, jumbo					313	20.9					352	24.6					432	18.1	2.21	66.4%	
DBM 1208 +/-45/M	double bias +/-45 plus mat	126	9.3	135	10.1	280	13.4					215	11.7	243	8.4	309	9.7	415	12.1	0.97	45.0%	652
DBM 1708 +/-45/M	double bias +/-45 plus mat					249	15.2					338	14.1					476	13.6	0.99	51.5%	855
DBM 1708 +/-45/M	double bias +/-45 plus mat					252	13.4					268	14.5					437	12.8	1.27	45.0%	855

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m^2
Owens Corning Knytex Reinforcements																						
DBM2408A	double bias +/-45 plus mat					228	14.9											450	12.5	1.27	53.2%	
XDBM1703	exp. double bias +/-45 & mat					132	9.4					236	12.3					323	8.3	1.42	39.7%	
XDBM1705	exp. double bias +/-45 & mat					94	7.6					138	10.7					238	7.2	1.30	35.4%	
XDBM1708F	exp. double bias +/-45 & mat					216	13.1					292	16.8					422	12.4	1.02	50.1%	
CDB 200 0/+/-45	warp triaxial	312	15.4			168	13.7	254	14.9			232	13.0	505	17.0			300	13.7	0.99	50.0%	757
CDB 340 0/+/-45	warp triaxial	333	16.7			176	12.8	278	15.3			172	13.6	493	16.2			239	13.0	1.40	50.0%	1061
CDB 340B 0/+/-45	warp triaxial, promat stich	252	16.9			155	12.8	229	15.7			201	12.1	491	14.5			245	11.9	1.50	50.0%	1132
CDM 1808 0/90/M	promat (0/90 plus mat)	256	14.5	208	12.6			208	12.6	195	10.0			421	15.9	339	13.3			1.37	45.0%	913
CDM 1808 B	promat (0/90 plus mat)	296	17.2					412	17.8					520	17.8					1.19	55.2%	987
CDM 1815 0/90/M	promat (0/90 plus mat)	236	14.2	190	11.8			196	12.0	188	11.4			385	11.7	367	10.0			1.75	45.0%	1112
CDM 1815B	promat (0/90 plus mat)	280	17.4					377	16.1					477	16.5					1.27	55.8%	1186
CDM 2408 0/90/M	promat (0/90 plus mat)	245	14.6	215	13.2			246	14.0	239	12.9			496	16.8	422	13.9			1.75	45.0%	1119
CDM 2408A	promat (0/90 plus mat)	338	18.9					440	14.3					616	19.1					1.22	56.5%	1153
CDM 2410 0/90/M	promat (0/90 plus mat)	256	15.2	243	13.2			208	12.9	196	11.4			425	14.6	345	13.0			1.78	45.0%	1166
CDM 2415 0/90/M	promat (0/90 plus mat)	243	14.2	214	13.6			216	13.6	188	12.4			404	13.4	403	12.8			2.11	45.0%	1318
CDM 2415	promat (0/90 plus mat)	329	17.2	340	16.6			342	18.5	334	18.0			497	14.2	535	15.9			1.42	54.9%	
CDM 2415A	promat (0/90 plus mat)	231	15.2					486	17.2					505	16.3	381	12.0			1.50	54.6%	1338
CDM 3208	promat (0/90 plus mat)	308	17.0					455	19.4					583	17.7					1.40	60.2%	1352
CDM 3610	promat (0/90 plus mat)	364	19.9					360	21.7					643	16.4					1.42	38.2%	
CDM 3610 ST	promat (0/90 plus mat)	355	18.9					326	22.3					625	15.9					1.40	39.6%	
CDM 4408	promat (0/90 plus mat)	317	16.9	294	18.9			345	16.9	400	18.9			440	16.1	579	21.0				54.6%	
XCDM 2315	exp promat (0/90 plus mat)	252	14.5	248	14.5									491	13.9	405	12.2			1.52	54.9%	
DDB222	weft triaxial	265	17.6			154	9.7	229	14.1			197	13.0	396	14.5			290	12.2	0.99	50.0%	747
DDB340	weft triaxial	331	16.9			162	9.2	234	15.4			191	13.3	452	15.4			339	12.6	1.50	50.0%	1142
XDDBM2208	exp weft triaxial w/ mat			264	15.1	135	11.0													1.30	48.9%	
XDDM2710	exp stichbonded weft triaxial w/ mat			301	16.0	152	10.9													1.40	53.6%	
XDDB222	exp stichbonded weft triaxial	86	8.0	377	18.6									175	8.8	541	17.8			0.76		
XDDB340	exp stichbonded weft triaxial	83	7.8	490	22.0									176	9.0	657	22.0			0.99		
GDB 095 +/-45 carbon	double bias +/-45 carbon					462	34.3					359	31.3					621	19.1		50.0%	331
GDB 095 +/-45 carbon	double bias +/-45 carbon					622	31.6					403	20.5					596	14.8	0.51	50.0%	331
GDB 120 +/-45 carbon	double bias +/-45 carbon					462	42.7					193	40.3					710	23.4		50.0%	416
GDB 120 +/-45 carbon	double bias +/-45 carbon					528	36.4					307	16.5					554	15.4	0.64	50.0%	416
GDB 200 +/-45 carbon	double bias +/-45 carbon					400	47.8					124	38.4					538	21.0		50.0%	669

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m²
Owens Corning Knytex Reinforcements																						
GDB 200 +/-45 carbon	**double bias +/-45 carbon**					503	39.0					284	24.5					659	18.3	1.02	50.0%	669
KDB 170 +/-45 Kevlar	**double bias +/-45 Kevlar®**					352	22.3					83						234			50.0%	537
17MPX						259	15.2					224	11.8					412	11.9	0.79	50.0%	
XH120		408	24.8					207	17.4					311	11.4					1.42	50.0%	
XH120						121	9.9					120	12.3					152	8.3	1.42	50.0%	
CDDB310	**quadraxial**	235	12.5	218	13.3			254	12.9	215	12.8			395	10.3	346	9.5			1.17	55.0%	
CDB 340 0/+/-45	**warp triaxial**	331	18.0					234	15.6					462	14.2						55.0%	1061
CDM 2410 0/90/M	**promat**	255	15.9					186	12.9					372	9.7						45.0%	1166
GA 045 Uni carbon	**woven warp unidirectional, carbon**	669	64.4					524	81.0					1344	61.9						55.0%	155
GA 080 Uni carbon	**woven warp unidirectional, carbon**	1685	126.2											936	75.2						48.0%	
GA 090 Uni carbon	**woven warp unidirectional, carbon**	1606	130.3											1197	100.0					0.38	58.0%	318
GA 130 Uni carbon	**woven warp unidirectional, carbon**	1618	125.5											1040	84.1					0.46	64.0%	
KBM 1308A	**woven Kevlar®/glass hybrid plus mat**	333	17.1											323	15.1					0.76		
Kevlar/Glass Hybrid		293	15.7	258	14.8									402	14.7					0.69		
KDB 110 +/-45 Kevlar	**double bias, Kevlar®**					386	25.1					103	9.1					338	7.7		45.0%	352
KDB 110 +/-45 Kevlar	**double bias, Kevlar®**					508	20.7					137	9.0					453	13.5	0.58	50.0%	352
KB 203 WR E-glass/Kevlar	**woven Kevlar®/glass hybrid**	455	37.8					145	23.9					352	16.7						45.0%	703
SDB 120 S-glass	**double bias, S-glass**	434	20.9					310	20.0					487	13.0						55.0%	385
SDB 120 S-glass	**double bias, S-glass**	414	16.2					319	14.5					540	15.4					0.53	50.0%	581
B238	**starch oil woven roving**	218	13.2	194	12.4			197	12.4	184	12.1			336	12.8	305	12.3			1.45	40.0%	
B238+.75 oz mat	**starch oil woven roving w/ mat**	190	12.3	173	11.6			185	12.3	169	11.9			290	12.4	274	11.8			2.18	35.0%	
Spectra 900	**Spectra**	439	19.7	373	18.3			130	14.1	114	13.0			334	12.4	305	11.9			0.43	50.0%	
K49/13 Kevlar	**Kevlar® 49**	357	19.9	337	19.2			136	16.2	121	14.5			291	10.3	270	9.9			0.69	45.0%	

Reinforcement Description		Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
		MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gms/m²
DuPont Kevlar Reinforcements																						
Kevlar 49 243	unidirectional	552	37.4											239	26.5							226
Kevlar 49 243	unidirectional	626	45.5											347	33.4							226
Kevlar 49 281	woven cloth	412	22.3											221	17.5							169
Kevlar 49 281	woven cloth	418	25.8											252	21.8							169
Kevlar 49 285	woven cloth	338	19.0											217	16.3							169
Kevlar 49 285	woven cloth	407	22.2											283	19.4							169
Kevlar 49 328	woven cloth	439	21.4											162	17.9							213
Kevlar 49 500	woven cloth	356	20.5											261	14.2							169
Kevlar 49 500	woven cloth	381	25.7											349	19.5							169
Kevlar 49 1050	woven roving	308	21.6											185	13.9							355
Kevlar 49 1050	woven roving	412	20.5											244	18.2							355
Kevlar 49 1033	woven roving	350	24.5											155	15.3							507
Kevlar 49 1033	woven roving	361	23.6											237	18.4							507
Kevlar 49 1350	woven roving	448	53.1											202	21.7							456
Kevlar 49 118	woven roving	612												421	42.1							270
Kevlar 49/E-glass KBM 1308	woven/mat	240	12.3	232	12.6			170	16.1	175	13.4			259	9.9	256	10.1					630
Kevlar 49/E-glass KBM 2808	woven/mat	269	14.6	233	13.8			153	15.1	153	16.5			300	12.1	253	12.1					1120
Kevlar 49/E-glass C77K/235		269	14.6	233	13.8									300	11.7	253	12.1				45.0%	1122
Anchor Reinforcements																						
Ancaref C160 carbon, 12K	unidirectional	876	82.7					621	62.1											0.10	50.0%	159
Ancaref C160 carbon, 12K	unidirectional	1724	144.8					1103	137.9											0.08	70.0%	159
Ancaref C320 carbon, 12K	unidirectional	862	82.7					621	62.1											0.53		321
Ancaref C440 carbon, 12K	unidirectional	614	36.5					214	26.2											0.36		206
Ancaref S275 S-2 glass, O-C	unidirectional	889	37.9					427												0.23	60.0%	274
Ancaref S275 S-2 glass, O-C	unidirectional	2055	51.7					820	53.8											0.18	75.0%	274
Ancaref S160 S-2 glass, O-C	unidirectional	883	37.9					427	53.1											0.18		162
Ancaref G230 E-glass	unidirectional	524	29.6					545	21.4											0.36		321
Unidirectionals																						
High-strength, uni tape carbon	unidirectional	1241	144.8	55	11.7	160	16.1	1241	144.8	207	11.7	165	16.1									
High-strength, uni tape carbon	unidirectional	1241	128.9	28	6.0	91	8.3	483	128.9	83	6.0	94	8.3									
High-modulus, uni tape carbon	unidirectional	758	172.4	28	11.7	117	16.4	689	172.4	138	11.7	124	16.4									
High-modulus, uni tape carbon	unidirectional	662	166.2	21	5.9	50	12.8	414	166.2	55	5.9	50	12.8									
Intermediate-strength, uni tape carbon	unidirectional	1103	117.2	52	11.7			1103	117.2	172	11.7											
Intermediate-strength, uni tape carbon	unidirectional	993	110.3	28	6.9			448	110.3	103	6.9											
Unidirectional tape Kevlar	unidirectional	1172	69.6	28	5.5			276	69.6	138	5.5											

Reinforcement Description	Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gm/m^2
SCRIMP Process Laminates																					
Cert'teed/Seemann 625 WR							301						487						0.61	73.0%	811
Cert'teed/Seemann 625 WR	394						359						548						0.61	73.0%	811
Hexcell 8HS, Style 7781	392	23.4					401						576						0.25	66.0%	287
FGI/Seemann 3X1, 10 Twill	370	23.4					425						529						0.25	70.0%	324
8HS, 3K XaSg, 1029 carbon	676	57.2					255						481						0.41		368
8HS, 3K, 1029(UC309) carbon							290						470						0.41		368
5HS, 12K, 1059(AS4W) carbon		54.5					203						415						0.56		524
Hexcell CD180 stiched biaxial	345	22.1					286						412						0.66	64.0%	656
Chomarat 2 x 2 weave	277	20.0					379						478						0.79	61.0%	811
DF14OO	325	26.9	241	23.4			271		239				423		319				1.07	66.0%	1352
G:CI029 hybrid E-glass/carbon	490	44.1					274						665						1.02		
G:CI059 hybrid E-glass/carbon	443	42.1					200						685						1.02		
G:K285(60%) hybrid E-glass/Kevlar							164						520						1.22		
G:K900(40%) hybrid E-glass/Kevlar							253						510						0.84		
G:K900(50%) hybrid E-glass/Kevlar	396	25.5					219						432						0.97		
G:S985(40%) hybrid E-glass/Spectra	355	21.4					242						541						0.84		
DuPont 5HS, K49, Kevlar (900)	479	29.6					109						245						0.43		
Allied-Signal 8HS, S1000, Spectra (985)		14.5					59						128						0.25		186
Cert'teed/Seemann 625 WR	356	24.1					330						496						0.61	73.0%	811
Cert'teed/Seemann twill, 3X1	354	21.4					365						545						0.66	71.0%	811
Cert'teed/Seemann 625 WR	308	24.8					212						336						0.61	73.0%	811
Cert'teed/Seemann 625 WR	355	26.9					226						379						0.61	73.0%	811
Cert'teed/Seemann 625 WR	336	26.9					222						401						0.61	73.0%	811
5HS, 6K, 1030 carbon	634	58.6					394						684						0.38		345
5HS, 12K, 1059 carbon (AS4W)	615	57.2					445						690						0.56		524
Low-Temperature Cure Prepregs																					
Advanced Comp Grp/LTM21	524	29.0					413						516							77.9%	811
Advanced Comp Grp/LTM22	438	23.4					336						478						0.23	65.9%	301
Advanced Comp Grp/LTM22	467	24.1					353						507						0.23	66.9%	301
SP Systems/Ampreg 75	426	21.4					419						563						0.23	65.5%	301
SP Systems/Ampreg 75	456	22.8					440						621						0.23	62.8%	301
DSM Italia/Neoxil	345	19.3					473						601						0.23	57.0%	301
Newport Adhesives/NB-1101	349	20.0					393						472						0.23	60.3%	301
Newport Adhesives/NB-1101	333	20.7					430						480						0.23	60.3%	301
Newport Adhesives/NB-1107	402	22.8					408						518						0.23	63.3%	301
Newport Adhesives/NB-1107	332	15.9					333						399						0.23	63.3%	301
Ciba Composite/M10E	370	22.8					359						532						0.23	62.8%	301
Ciba Composite/M10E	645	63.4					305						592						0.23		301
YLA, Inc./RS-1	357	21.4					358						488						0.23	64.7%	301
YLA, Inc./RS-1	354	20.7					370						473						0.23	64.8%	301

Reinforcement Description	Tensile Strength: Longitudinal	Tensile Modulus: Longitudinal	Tensile Strength: Transverse	Tensile Modulus: Transverse	Tensile Strength: Diagonal	Tensile Modulus: Diagonal	Compressive Strength: Longitudinal	Compressive Modulus: Longitudinal	Compressive Strength: Transverse	Compressive Modulus: Transverse	Compressive Strength: Diagonal	Compressive Modulus: Diagonal	Flexural Strength: Longitudinal	Flexural Modulus: Longitudinal	Flexural Strength: Transverse	Flexural Modulus: Transverse	Flexural Strength: Diagonal	Flexural Modulus: Diagonal	Thickness Per Ply	% Fiber by Weight	Fiber Weight
	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	MPa	GPa	mm	%	gm/m^2
YLA, Inc./RS-1	381	20.7					385						492						0.23	63.6%	301
3M/SP377	289	21.4					390						412						0.23	63.1%	301
3M/SP377	296	22.8					410						410						0.23	64.4%	301
3M/SP365	243						259						337						0.41	68.5%	544
3M/SP365	326						408						492						0.41	69.5%	544
Fibercote Industries/E-761E	381	23.4					435						523						0.41	62.4%	544
Fibercote Industries/E-761E	402	24.1					455						542						0.41	62.6%	544
Fibercote Industries/P-601	423	22.8					443						603						0.64	57.0%	608
Fibercote Industries/P-601	442	23.4					484						625						0.64	60.3%	608
Fibercote Industries/P-600	376	20.0					296						460						0.23	62.6%	301
Fibercote Industries/P-600	405	21.4					349						543						0.23	64.7%	301
ICI Fiberite/MXB-9420	421	20.0					347						464						0.23	60.9%	301
Fiber Content Study for GLCC																					
Owens-Corning WR	307	20.6					315	22.8					405	15.8					0.64	52.4%	608
ATI NEWF 180 Biaxial	358	22.7					356	24.4					519	18.3					0.76	47.8%	608
Owens-Corning WR	397	25.4					320	24.6					565	19.8					0.64	61.0%	608
ATI NEWF 180 Biaxial	389	22.4					422	24.4					565	19.5					0.76	53.1%	608
Owens-Corning WR	403	25.7					322	25.1					646	22.7					0.64	66.9%	608
ATI NEWF 180 Biaxial	421	23.5					386	24.5					576	18.8					0.76	61.8%	608